THE NATURE OF THE WORLD AND OF MAN

By

W. C. ALLEE, G. W. BARTELMEZ, J. H. BRETZ
A. J. CARLSON, R. T. CHAMBERLIN, F.-C. COLE
M. C. COULTER, H. C. COWLES, E. R. DOWNING
E. O. JORDAN, C. H. JUDD, H. B. LEMON
F. R. MOULTON, H. H. NEWMAN
A. S. ROMER, *and* J. ST[illegible]ITZ

H. H. NEWMAN
Editor

Profusely Illustrated

GARDEN CITY PUBLISHING COMPANY, INC.

GARDEN CITY, NEW YORK

PRINTED AT THE *Country Life Press*, GARDEN CITY, N. Y., U. S. A.

shed September, 1926
mpression December, 1926
Third Impression March, 1927
Second Edition August, 1927

STAR EDITION
JANUARY, 1933
REVISED

PREFACE

The purpose of this book is to present an outline of our knowledge of the physical and the biological world, and to show the position of man in the universe in which he lives. Or, in more personal terms, it aims to assist the individual in the very important problem of forming well-defined conceptions of the Cosmos and of his relation to it.

Not only the aims of this volume, but also the plan on which it has been written, have been determined in large part by the fact that it contains the subject matter of a "survey course" given each year by its authors at the University of Chicago to a group of selected first-year students of superior intelligence. The survey course was designed to give capable students a preliminary view of the rich intellectual fields that lie before them so that, on the one hand, all of their work shall have a large measure of unity and coherence, and, on the other hand, they will be able to decide early what particular subjects they may wish more thoroughly to explore.

The course as given at the University of Chicago was initiated by Dean Ernest H. Wilkins, and it was organized by H. H. Newman, who has acted as director. Formal lectures have been given by sixteen instructors, each a specialist in his field. Each lecturer has conducted also a conference in his subject. Detailed class exercises and written reports have been directed by H. H. Newman, J Harlen Bretz, and Merle C. Coulter. The success of this educational experiment, from the standpoint of both instructors and students, has seemed to make advisable the production of this volume.

The aims of the course and the severe restrictions of space have made it necessary for the authors to omit largely those technical scaffoldings by means of which their respective scientific

structures have been erected. Generally they have been compelled to limit themselves to explaining final conclusions, but occasionally, when it has seemed feasible, they have given brief accounts of the means by which these conclusions have been reached. It is regretted that it has not been possible more frequently to show in detail the workings of the scientific method. It is believed, however, that these deficiencies are made up, at least in part, by the outside reading that is required, and that is regarded as essential for all who use this book. A list of books for accessory reading is appended to each chapter.

The authors of this book have not treated science as something cold and austere and apart from human life. On the contrary, it glows with the burning enthusiasm of those who have cultivated it; it is severe only in the standards of truth that it maintains; and it has aesthetic aspects as well as practical. There has been no hesitation in pointing out the present great value of science to mankind and the hopes for better things that it promises for the future.

During a period of four months the authors have spent one evening a week in conference on their completed manuscripts. Each author has read his chapter before his associates for their suggestions and criticisms, which have been numerous and valuable. Moreover, each chapter has been critically examined by at least one person beside its author and the editor. Although there has been an unusual amount of close co-operation in the preparation of this book, each author is responsible only for the chapter he has written.

The book is directly due to the inspiration from students, eager to learn, able to discern evidence, and prepared to face facts without fear. To these students and to other seekers of truth, outside as well as inside the colleges, this book is affectionately and hopefully dedicated by

THE AUTHORS

PREFACE TO THE SECOND EDITION

Since the publication of the first edition we have had the benefit of constructive criticism from specialists who have used *The Nature of the World and of Man* as a textbook in large classes. Many of the suggestions made have been incorporated in this revision, and we have included also changes recommended by the authors as a result of additional classroom use. The book is a co-operative undertaking, and we plan to revise it frequently in order to keep it abreast of the best educational practice and the most recent advances in science.

The most important changes will be found in the chapter on "The Nature of Chemical Processes," which now appears in a much less difficult form, and in the chapters on "Energy: Radiation and Atomic Structure" and "Man from the Point of View of His Development and Structure." Minor changes have been made in several other chapters, and both Glossary and Index have been enlarged.

Further criticism and suggestions will receive careful attention.

H. H. NEWMAN, *Editor*

ACKNOWLEDGMENTS

It is a pleasure to acknowledge our indebtedness to all those authors, publishers, and artists whose co-operation has helped to make this volume possible.

Among the artists who have contributed to this book, especial mention should be made of Mr. Carl F. Groneman, who illustrated Professor Cole's chapter, using original material borrowed from Logan Museum, Beloit College, and from the Field Museum of Natural History; and of Mr. Kenji Toda, artist of the Department of Zoölogy, who drew most of the figures in Professor Allee's chapter.

We wish to thank the Macmillan Company for the use of Figures 24, 25, 26, 27, and 118 (from *The Cell in Development and Heredity*, E. B. Wilson, 1925), Figures 42, 43, 46, 49, 54, 71, 75, and 77 (from *Outlines of General Zoölogy*, H. H. Newman, 1924), Figure 23 (from *College Zoölogy*, R. W. Hegner) and Figure 65 (from *Medical and Veterinary Entomology*, W. B. Herms, 1923); the American Book Company for Figure 74 (from *Geology*, H. F. Cleland); the McGraw-Hill Company for Figures 119 and 120 (from *Genetics in Relation to Agriculture*, E. B. Babcock and R. E. Clausen, 1918), and for Table IV (from *Introduction to General Chemistry*, McCoy and Terry); W. B. Saunders Co. for Figures 28, 30, and 31; John Wiley & Sons for Figure 29; Ginn & Co. for Figures 130, 131, and 132 (from *Psychology, General Introduction*, C. H. Judd, 1917); Cambridge University Press for Figure 104; and the United States Geological Survey for Figure 15.

THE EDITOR

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER I

ASTRONOMY

FOREST RAY MOULTON

1. Introduction. *Arma virumque cano* (I sing of arms and of a man)—thus Vergil began his great epic poem upon the adventures of Aeneas of Troy.

The Nature of the World and of Man is a greater theme by far than that of the Roman poet. On its physical side, it is not limited to a circumscribed area on the shores of the Mediterranean, but it ranges from electrons up through atoms to molecules and to worlds and to suns and to galaxies of suns. In time, it covers not simply the brief span of a part of a human life, but it reaches back to the origin of worlds and traces the outline of their development down through the geologic ages to the present, and it looks forward to a distant future when they will come to an end. It is not concerned merely with a few adventurers from the shores of Troy, but it includes myriads of types of plants and of animals from the lowliest bacteria and protozoa up to man. It does not recount the great deeds of only one hero and his companions, but it is the story of the efforts of the human race to conquer the physical world, to learn how to live happily with itself, and to direct its own improvement.

The Nature of the World and of Man is not only a great subject—in fact, the greatest one that human beings may investigate—but it is one rich in romance and filled with stirring adventure. It will satisfy, if anything can, the love of youth for heroic things. The giants of mythological days are far surpassed by the huge machines that are the untiring slaves of modern men. The eye of fabled Cyclops was not even prophetic of the great telescope on Mount Wilson, the pupil of whose eye, so to speak, is 100 inches in diameter. Not all the magic of antiquity can match the mar-

vels of any chemical laboratory. Physicians cast out demons by means of surgery, by the use of extracts of ductless glands, and by prescribing chemical compounds; and, if they have not raised the dead even in a single instance, they have at least within a few decades increased the average span of human life by ten or fifteen years. The cryptic prophecies of the oracles have been succeeded by precise predictions of eclipses and the returns of comets and corresponding things in every domain of science. In fact, reason and the laws of nature (mark well *reason* and the *laws of nature*) have become a sort of intellectual telescope, as it were, with which modern science looks back across the geological ages and discerns, at least in outline, the chief steps of the evolution of the inanimate and of the organic world; and, similarly, penetrates the future to a time when this earth will cease to be suited for the abode of life. Not all of the adventures in this subject, however, are in the domain of the material world, or even the intellectual; its moral conquests are as numerous and as inspiring. Many a chemist, physicist, biologist, psychologist, and historian, as well as monk, has had as his first and only love The Truth, and as his greatest reward the approval of his own conscience.

The Nature of the World and of Man is not a field of adventure that was exhausted long ago. On the contrary, every discovery that has extended the circle of the known has increased the opportunities for making new discoveries by enlarging the perimeter of the unknown that surrounds it. Although more discoveries have been made in nearly every branch of science in the last two or three decades than in all the previous history of mankind, the questions awaiting answers were never before so numerous; and, likewise, the increasing complexities of human relationships present new problems of correspondingly great difficulty and importance.

This is a world of stern realities and this is a practical age. The Nature of the World and of Man deals with stern realities and it is of the highest practical value. Its whole purpose is tc acquaint one with the nature of the environment in which he is and in which his life will be spent. It is a deliberate attempt to do

well that which every person does more or less subconsciously for himself, namely, to build up some sort of mental picture of the Cosmos and of the place of man in it. Everyone has some such picture which serves him as a basic philosophy of life in terms of which he interprets events and in harmony with which he orders his own actions. It is, in fact, his character.

There is in Glacier Park a spot at which the waters divide, one part winding its long way to the Pacific Ocean, a second to the Gulf of Mexico, and the third to Hudson's Bay. Many a person has stood in awe at that place and reflected upon the fact that the difference of an inch in the beginning makes a difference of thousands of miles in the distant goal. The corresponding point in the life of a student is his Freshman year before the currents of his intellectual life have become strongly established. The Nature of the World and of Man aims to give him a preliminary view of his surrounding world and of his possible function in it. Consequently, it is evident that nothing could be of greater importance for him. It is fortunate that in this subject romance joins with reality and that great adventure is found often to contribute to the welfare of mankind.

2. **Science.**—Within a few decades the world has been revolutionized by science and its applications. A hundred years ago civilized men were only about one-fourth as efficient in the production of the necessities and the luxuries of life as they are today. Science not only provides better food and clothing and shelter than mankind ever before enjoyed, but it makes possible our abundant leisure for recreation and cultivating our higher faculties. Most of the 800,000 students now in the higher institutions of learning in this country owe their unparalleled opportunities to science. In the long run it will probably be found that the greatest benefit of science to the human race has been not in providing the material things of life, but in furnishing unlimited opportunities for cultivating the intellectual.

The successes of science invite attention to its methods. That science depends upon observations and experiments is known to

everyone, but those who have not been engaged in its pursuit cannot fully realize the scrupulous care with which observations and experiments are made, the faithfulness with which they are recorded, the variety of conditions under which they are repeated, and the caution with which conclusions are drawn from them. Science does not bow down before precedent nor custom nor dogma; it exalts the truth and honestly seeks it. The fact that scientific theories have often been altered justifies no reproach to science, for they are simply the most coherent organizations of its data that are possible at a given time. The fact that changes are necessary means that knowledge has been increased. New discoveries do not contradict earlier truth, but include it as a special case, or as an imperfect statement of some larger truth. For example, the recent discovery that atoms are composed of positive and negative electrons does not overthrow chemistry although some of its terminology is changed.

The basis on which science rests is the orderliness of the universe. This means that similar initial conditions are always followed by similar sequences of phenomena—in popular terms, a given cause under given conditions always produces the same result. This proposition is so simple that it often seems almost axiomatic, but the history of mankind proves that such is far from being the case. The numerous capricious gods and goddesses of mythological days were invented to explain the phenomena of a universe whose orderliness was not perceived, and the superstitions of the present time are evidence that the underlying principle on which science rests is unfortunately not yet universally accepted.

Science had its beginnings before the dawn of recorded history, probably in the civilizations that flourished in the valleys of the Nile and the Euphrates rivers. The earliest approach to science was in astronomy, for in this domain several relatively simple and frequently recurring celestial phenomena, such as the phases of the moon, first impressed men with the fact that the universe is orderly. The earliest writings that have come down to us contain

numerous references to orderly and majestic celestial phenomena. The brilliant and energetic Greeks began systematic astronomical observations several centuries before the beginning of the Christian Era and determined with considerable approximation the periods of the moon and the earth, and they explained correctly the causes of eclipses and developed methods of predicting them. After the principle of the orderliness of the universe had been established in one science, it became much easier to extend it to all the others. Although for some centuries during the Dark Ages science stood still while civilization flickered and seemed to be on the point of being extinguished, yet on the whole the principle of the orderliness of the universe has been steadily extended from astronomy and physics and chemistry and the other sciences dealing with the inorganic world to the biological sciences, and more recently to psychology and history and sociology and everything else connected with the mind of man. It should be insisted at once that knowledge of the order of the physical universe is very imperfect, to say nothing of the more complicated biological domains and the infinite intricacies of psychological phenomena. The point is simply that there is abundant evidence to support the conclusion that there is orderliness in all of these fields and to emphasize the fact that scientists universally hold such a belief.

3. **The earth as an astronomical body.**—Since science had its origin in observations of celestial phenomena, and since astronomy was centuries old before the first steps were taken in many other sciences, it is appropriate that a study of the Nature of the World and of Man should start with what has been learned in a large way of the Cosmos. There are, however, other equally important reasons why this discussion should begin with astronomy. The first is that it will help to place our earth in proper perspective with the great physical universe of which it is a minute part, just as a map of a country will show the location of a particular city which one may wish to examine in detail. Another reason is that astronomy illustrates most simply scientific procedure in a domain in which truth has always been pur-

sued with the loftiest motives, and in connection with which there has never been anything that has been mean or low or sordid. A third reason is that some of its laws are not only very easy to understand, but have been established with a degree of certainty that is scarcely approached in other domains of human endeavor.

The earth is the most accessible astronomical body, and a start on the exploration of the celestial regions must be made from it. Only yesterday our predecessors thought it a vast plane and the principal object of creation, but the voyages of courageous sailors corrected the error. Then, by a combination of measurements of arcs on the earth's surface and astronomical observations, its size and shape were determined with an error not exceeding 1 part in 50,000. In round numbers, the diameter of the earth is about 8,000 miles, and the equatorial diameter is 27 miles greater than the polar.

The part of the earth that can be directly examined is a relatively thin surface layer. If the earth were represented by a globe eight inches in diameter, the deepest mines would not reach to a depth of one-thousandth of an inch. In fact, the origin of volcanic lavas would probably be less than one three-hundredth of an inch below the surface. At first thought it might be supposed that man must forever remain ignorant of the deep interior of the earth, but science often achieves that which seems impossible. By comparing the attraction of the earth with that of a known ball (a very difficult experiment from the practical point of view), it has been proved that the average density of the earth is about 5.5 times that of water. This means that its total mass is 6×10^{21} tons.

Not only has the average density of the earth been determined, but the physical condition of its interior is now known. The temperature rises with descent into earth at a rate averaging something like one degree Fahrenheit for every seventy-five feet. It follows that the temperature of the interior of the earth is very high, probably thousands of degrees. This fact led our predecessors to the conclusion that the interior of the earth is probably fluid, and "the crust of the earth" was an often-used expression.

But marvelous experiments (tide-experiments) by Michelson and Gale, started in 1913, which measured the resistance of the earth as a whole to the tide-deforming forces of the moon, enabled mathematicians to prove that the earth through and through is on the average as rigid as steel. Moreover, it is elastic, like steel, rather than viscous, like stiff pitch.

4. **The moon.**—The earth's nearest neighbor and satellite is the moon. After the size of our globe had been determined, the distance of the moon could be found by observing its apparent direction from two points on the earth. The measurement depends only upon some accurate determinations of angles and upon

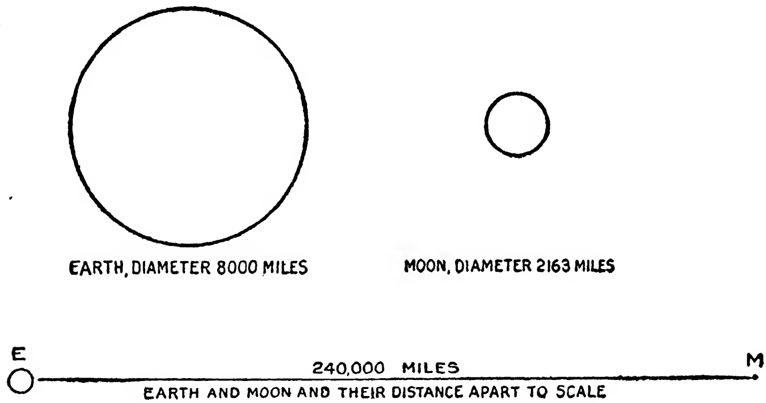


FIG. 1.—The earth and moon on same scale

trigonometrical calculations. In round numbers, the average distance from the center of the earth to the center of the moon is 240,000 miles, the possible error in the determination not exceeding one-hundredth of 1 per cent.

The diameter of the moon is 2,163 miles, its size relative to the earth being shown in Figure 1. The moon is only 60 per cent as dense as the earth and its mass is only one-eightieth that of the earth.

A consequence of the small mass of the moon is that its sur-

face gravity is only about one-sixth that of the earth; that is, a body that would weigh one pound by spring balances on the surface of the moon would weigh six pounds on the surface of the earth. A mass thrown upward from the surface of the moon with a given velocity would rise six times as high as it would if it were thrown up from the surface of the earth with the same velocity. There is, of course, no one on the surface of the moon to throw masses upward, but the same principles apply to the innumerable particles of which an atmosphere is composed. Our air, for example, consists of molecules of nitrogen, oxygen, and a few other elements and compounds which are in such rapid motion that they keep up a pressure of fifteen pounds per square inch at sea-level in spite of the fact that the density of the atmosphere is only one eight-hundredth that of water. The molecules in our atmosphere at surface density and summer temperature have an average velocity of about 1,500 feet per second. They dart in every direction and collide with other molecules millions of times per second.

The moon has no atmosphere whatever nor any water upon its surface. The reason for this important difference between the earth and the moon is probably that the moon's surface gravity is too feeble to hold down near its surface rapidly darting atmospheric particles. This conclusion is supported by the observed fact that all known bodies having low surface gravities have no atmospheres, while all having surface gravities greater than that of the earth are surrounded by atmospheres.

Since the moon has neither atmosphere nor water there is no erosion upon its surface. The mountains have not been worn down, running water has cut no chasms, and the rocks have not been transformed into soil. The consequence is that the surface of the moon is a barren, lifeless place of eternal desolation and silence.

The moon rotates on its axis at the same rate that it advances in its orbit in its revolution around the earth, with the result that it always presents the same surface toward the earth. The

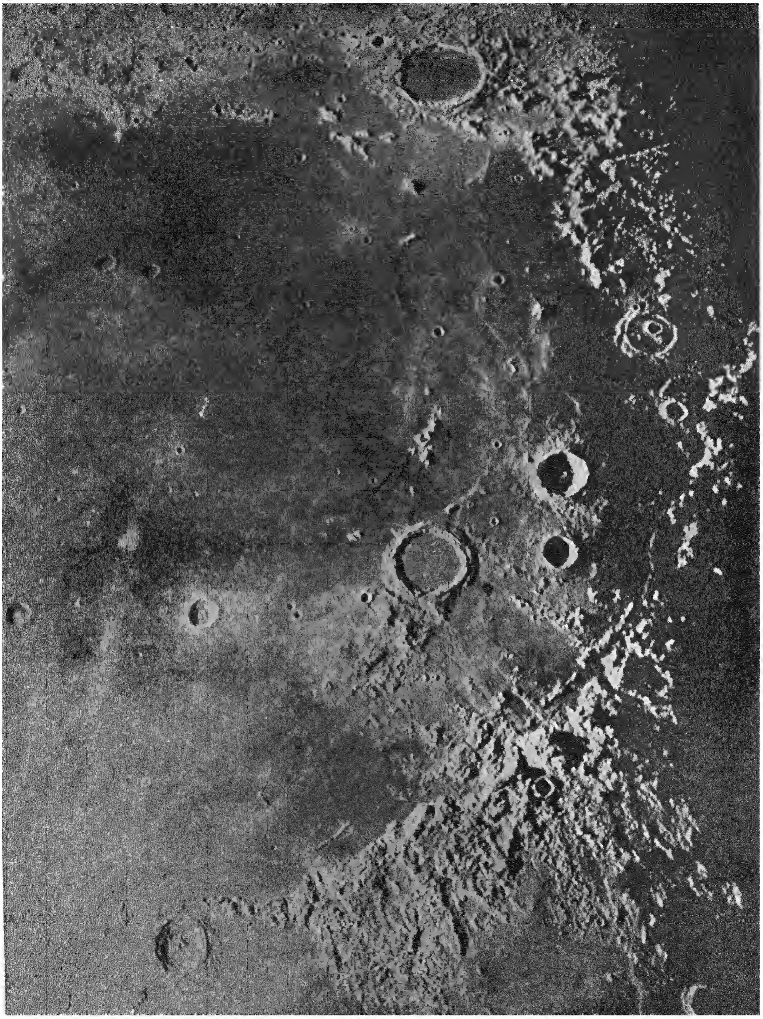


Fig. 2.—Photograph of lunar landscape with 100-inch reflector of the Mount Wilson Observatory.

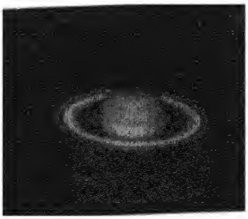


FIG. 7.—Photograph of planet Saturn with 100-inch reflector of the Mount Wilson Observatory. Diameter of rings, 175,000 miles; thickness, about 50 miles.

side of the moon visible from the earth (the other is almost certainly similar) is on the whole very rugged and largely covered with circular depressions, called craters, ranging from the limits of visibility up to immense objects over one hundred miles in diameter. There are, however, large relatively smooth areas that have few craters. In addition, there are several mountain ranges and many isolated peaks on the smooth areas, some of them rising very steeply from their bases to a height as great as 20,000 feet.

What a contrast the moon presents with the earth! They revolve about the sun together, and consequently they receive the same amount of light and heat per unit area from the sun. But here the similarity ends. The moon's day is nearly thirty of the earth's days in length and its surface is barren and lifeless. For nearly fifteen of our days it is baked by the sun's burning rays, never cut off by a passing cloud nor dimmed by an atmosphere. During the long day the temperature of the surface rocks rises nearly to the boiling-point of water. Then, when the sun sets, the temperature rapidly falls because there is no atmospheric blanket to hold in the heat. In two hours the freezing-point is reached, and then the temperature descends during the remainder of the long night (fifteen of the earth's days) to possibly 200° or 300° Fahrenheit below zero. Alternately freezing and roasting, the moon pursues its path about the earth throughout the long periods of geologic time, an illustration of what the earth would probably be like if its gravitation were not great enough to hold water and an atmosphere upon its surface.

The interest in the moon of astronomers does not terminate with a knowledge of its surface. Its motion is equally important, for it depends upon the laws of nature which must be understood and tested before progress can be made in such great problems as the origin and evolution of the planetary system. The orbit of the moon about the earth is roughly elliptical, but it has many hundreds of minor irregularities due to the attraction of the sun and of the equatorial bulge of the earth. The complexity of the problem is measured by the fact that Delaunay's expressions for

the distance, longitude, and latitude of the moon could not be printed in a volume the size of this one. What an answer for a problem! Yet the solution is so exact that astronomers predict eclipses with unfailing precision for as great a time as they wish. They could, for example, set a telescope now in some fixed position so that our successors a hundred years in the future could look through it on a specified date, hour, minute, and second and see the center of the moon's disk. This, of course, is not important except as it illustrates the accuracy of astronomers' knowledge of the laws of the motions of celestial bodies and the reliability of their mathematical processes.

5. **The planetary system.**—The distances to the planets and to the sun may be found by essentially the same method as that

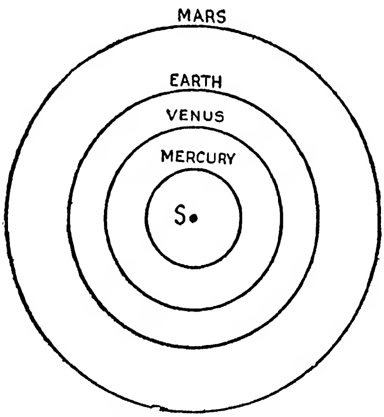


FIG. 3.—Orbits of first four planets to the same scale.

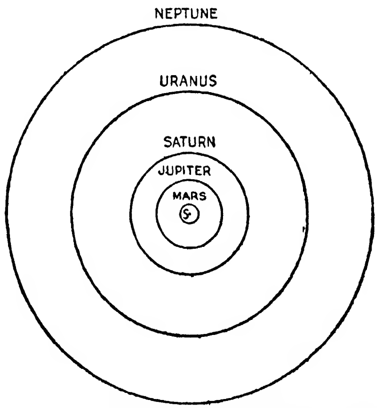


FIG. 4.—Orbits of outer planets to the same scale.

used in finding the distance to the moon. There are eight principal planets and about a thousand much smaller ones. The orbits of the first four are shown in Figure 3, and the outer ones beginning with the fourth, are shown in Figure 4. The orbits of the remote planets are so much larger than those nearest the sun that they cannot all be shown to scale on the same diagram. The table gives their distances from the sun, periods, etc.

The first four planets, known as the Terrestrial Planets, are in a general way similar to the earth. Their relative sizes are shown in Figure 5. Mercury is so small that it has no atmosphere, and the atmosphere of Mars is rare. On the other hand, the

Planet	Distance from Sun	Period	Mean Diameter	Density (Water = 1)	Mass (Earth = 1)
Mercury...	36,000,000 miles	2.9 months	3,009 miles	4.5 (?)	0.05 (?)
Venus	67,200,000 miles	7.4 months	7,701 miles	4.9 (?)	0.81 (?)
Earth.....	92,900,000 miles	12.0 months	7,918 miles	5.53	1.00
Mars.....	141,500,000 miles	22.6 months	4,339 miles	3.58	0.11
Jupiter....	483,300,000 miles	11.9 years	88,392 miles	1.25	314.5
Saturn....	886,000,000 miles	29.5 years	74,163 miles	0.63	94.1
Uranus...	1,781,900,000 miles	84.0 years	30,193 miles	1.44	14.4
Neptune...	2,791,600,000 miles	164.8 years	34,823 miles	1.09	16.7

atmosphere of Venus is so extensive and cloud-filled that the surface of this planet is invisible from the earth. Of the four, only Venus and Mars, besides the earth, are possibly in a condition such that life could flourish on their surfaces. Although Mars, because of its great distance from the sun, receives per unit area only about as much heat from the sun as the earth's poles receive (on the average), yet seasonal changes are observed on its surface, and its polar caps nearly disappear during its long summers.

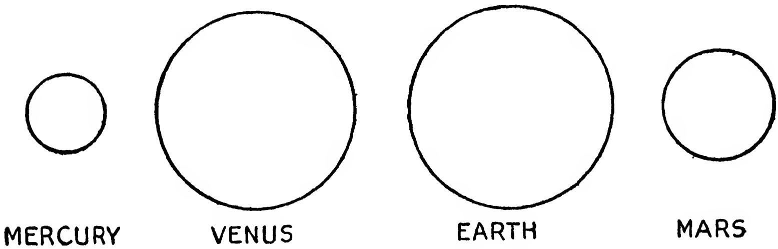


FIG. 5.—The earth like planets to same scale

Much has been written on the habitability and possible inhabitants of the planet Mars. That Mars supports some sort of life is not improbable, but there is no conclusive evidence to establish the theory nor to disprove it. When Mars and the earth are

nearest they are separated by about 40,000,000 miles, a distance that sound would require more than six years to traverse, and at such a great distance small features on its surface are invisible. If there is life on the planet Mars, the higher forms at least are quite different physically from the higher forms on the earth, for they are, and must be, more or less adapted to their widely different environments. Likewise if Mars is the abode of highly intelligent life, the stage of development of this life may correspond more nearly to that of our predecessors millions of years ago than to our own, or it may correspond more closely to that at which our successors will have arrived millions of years in the future. When

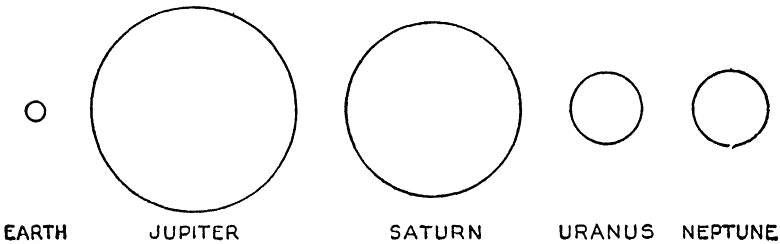


FIG. 6.—The earth and the major planets to the same scale

one thinks what revolutions in living science has wrought, and what changes in political institutions and social and economic relationships have taken place in the last few centuries, he pauses in awe before the possibilities of millions of years. Yet on Mars, or perhaps on other worlds, such stages of development may already have been reached. Although these thoughts are speculations, they are not useless if one does not fail to remember they are speculations, for such mental exercises help him to consider more objectively the varied problems of his own life.

The outermost four planets, the Great Planets, are enormous bodies compared to the earth. The largest of them, Jupiter, in volume is a thousand times greater than the earth. These planets are all very tenuous, probably being entirely in a gaseous state, and therefore not in a condition to support life. Even if they

were similar to the earth, they could not support life because even Jupiter receives less than one-tenth as much heat per unit area as is received by the earth's pole.

Saturn in some respects is the most interesting planet in the solar family. This giant world, 75,000 miles in diameter, is surrounded by an enormous ring system in the plane of its equator, the distance across the rings being about 175,000 miles. In spite of their great extent they are very thin, probably not exceeding 50 miles in thickness. The rings of Saturn are composed of innumerable small masses that circulate around the planet in independent paths. Their great number gives the rings the appearance of solidity, just as a cloud of minute drops of water appears as solid as the summit of a snow-capped mountain that it may be passing.

The Great Planets have numerous satellites, nine circulating about Jupiter and an equal number about Saturn. It is a remarkable fact that all the satellites of Jupiter except two, and all those of Saturn except one, revolve around their respective planets in the direction in which the planets rotate, while the exceptional satellites revolve in the retrograde direction.

Between the orbits of Mars and Jupiter there circulate about 1,000 known small planets ranging in size from minute objects at the limit of visibility with large telescopes, possibly 25 miles in diameter, to a few that are between 200 and 500 miles in diameter. The first of these bodies was discovered January 1, 1801, but most of them have been found by photography during the last 20 or 30 years. It seems probable that there are innumerable smaller ones beyond the range of present instruments. Several are known at about the distance of Jupiter, and there is one revolving within the orbit of Mars.

The planets Mercury, Venus, Earth, Mars, Jupiter, and Saturn have been known from prehistoric times, for they are all easily visible with the unaided eye, and Venus, Mars, and Jupiter are particularly conspicuous. About every nineteen months Venus is evening star for three or four months, a brilliant white object almost rivaling the moon in brightness. At other times it is

an equally glorious morning star. The somewhat less brilliant Jupiter and ruddy Mars are also sometimes called the evening or the morning star. Strictly speaking, to call any of them a star is an error, for they are only planets shining entirely by reflected light, while the stars are distant self-luminous suns a million times as large.

The planet Uranus, which is just beyond the range of the unaided eye, was discovered in 1781 by William Herschel. After the apparent position of a planet has been observed a few times its orbit can be determined and its position can be computed for any future time. The orbit of Uranus was computed from Herschel's observations, and for many years its computed positions agreed with those that were observed. Finally, in about 1821, forty years after its discovery, Uranus was not found exactly at its predicted places. By 1831 the discrepancies were larger; by 1841 they were intolerable to astronomers. This does not mean that theory said the planet would be found in one part of the sky and that observation showed it to be in a far distant part. As a matter of fact, the predicted and observed positions were so near each other that if a body had been at each of them they would have been seen by the unaided eye as a single object.

One would naturally inquire why the minute departure from its predicted place of an object that had been unknown during all the history of mankind until 1781 was anything of particular interest. Our world with all of its ills and pleasures would go on almost exactly the same even if Uranus should cease to exist. Does not this prove that astronomers are impractical and visionary?

The answer is the exact opposite to what would naturally be expected. The failure of such a prediction as that of the position of Uranus was not of importance in itself, but it called into question the correctness of such fundamental things as the laws of mechanics and the law of gravitation, and it challenged the validity of human reason. When any observation, however unimportant it may otherwise be, throws doubt upon the correctness of logic

and upon our ability to discover the laws of nature, it becomes of the greatest importance.

The discrepancy in the predicted motion of Uranus led to one of the most dramatic scientific discoveries ever made. It was suggested that the unexplained irregularities in the motions of the planet might be due to the slight attractions of an unknown and more remote planet. The problem was to find the location of the unknown planet from the accumulated effects of its attraction over a period of more than sixty years. The difficulties of the problem were so forbidding that the most experienced mathematicians of the time did not even attempt to solve it. Two young men, however, undertook what seemed a superhuman task and carried it to completion. Adams, an English student at Cambridge, and Leverrier, a young Frenchman, each wholly independent of the other and by different methods, reached out with their logic across nearly 3,000,000,000 miles and located the unknown world. A young German astronomer, named Galle, directing his telescope according to the instructions of Leverrier, within half an hour discovered the new planet, Neptune, almost exactly at its predicted place. Thus was human reason vindicated again and our confidence in our ability to learn the laws of nature was given new support.

Such discoveries as that of Neptune compensate us for the relatively unimportant place astronomy assigns to this little world on which we live. When these triumphs of our reason are considered objectively and from the point of view of possible human progress, the victories of the greatest military leaders the race has known shrink into comparative insignificance. With thoughts like these in mind, the epitaph over the tomb of Newton, in Westminster Abbey, where the English have buried their greatest and noblest dead, takes on new significance: "Mortals, congratulate yourselves that so great a man has lived for the honor of the human race." Let it be repeated: "Mortals, congratulate yourselves that so great a man has lived for the honor of the human race."

6. The sun.—In popular thought the sun and the moon are often associated as being comparable bodies. It is true that they appear to be about the same size, but when their distances are taken into account it is found that the volume of the sun is more than 60,000,000 times that of the moon. Even the light received by the earth from the sun is 600,000 times that received from the full moon. It is obvious that the moon is not an object that is suitable for comparison in attempting to get a correct mental picture of the sun.

The diameter of the sun is 864,000 miles—in round numbers 1,000,000 miles. In volume the sun is more than 1,000,000 times greater than the earth. Its density, however, is only 40 per cent

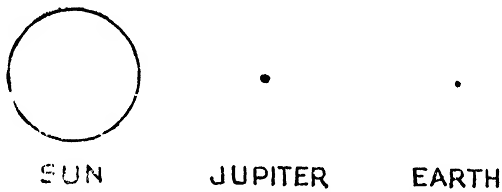


Fig. 8.—The sun, Jupiter, and the earth to the same scale; diameters, 864,000, 88,000, and 8,000 miles.

greater than that of water, and its mass consequently is about 300,000 times that of the earth. Even the giant planet Jupiter, 1,000 times greater than the earth in volume, is insignificant in comparison with the sun. If the earth could be placed at the center of the sun and the moon could continue to revolve about the earth, its orbit would be only a little more than halfway to the surface of the sun. All of the planets together have a mass of only one-seventh of 1 per cent of that of the sun. Consequently, the planets are seen to be comparatively unimportant bodies, except for the fact that we live on one of them and that it is on them alone that life can flourish. The relative dimensions of the earth, Jupiter, and the sun are shown in Figure 8.

The amount of light and heat (radiant energy) received by the earth from the sun is enormous. On a square yard exposed per-

pendicularly to the sun's rays radiant energy is received at the rate of one and one-half horse-power. The average rate for the earth through the periods of darkness as well as of light is three-eighths of a horse-power per square yard. This means that 300 horse-power are received on a building 50 by 150 feet in dimensions.

The radiant energy received from the sun is the source of practically all the forces that man directs upon the earth. The winds blow because the sun heats different portions of the earth's atmosphere unequally. There are waterfalls because the sun has evaporated and raised up into the air enormous quantities of water. When coal and petroleum burn they give up energy that plants received from the sun in bygone geological ages. When a man uses his muscle, or his brain, he is directing energies that were received by plants from the sun, perhaps transformed by some other animal before he uses them. Although the stored-up energies received from the sun in far-off geological ages may eventually be exhausted, there are still possibilities of having plenty, for our planet is receiving energy at the rate of 160,000 horse-power per inhabitant of the earth at the present time.

The earth as seen from the sun would look like a tiny speck, as small as Mars appears from the earth. Consequently the earth receives only an insignificant fraction of the energy the sun radiates; in fact, only one two-billionth. If the sun were created expressly to light and heat the earth, what a waste of energy! Not only is the total radiation of the sun inconceivably great, but the radiation per square yard is at the enormous rate of 70,000 horse-power. This means, of course, that the sun is very hot. At its radiating surface the temperature is 10,000° Fahrenheit, and the temperature in its deep interior is enormously higher. The sun, therefore, cannot be a solid nor even a liquid body. It is, on the contrary, a vast gaseous mass, the seat of tremendous energies, and it is torn by violent storms. Often masses of incandescent vapors, many times greater than the earth in volume, are driven about like ocean foam at the rate of several hundred miles per

minute, or are hurled aloft from its surface to a distance even twice as great as that from the earth to the moon. The earth has never been acted upon by such terrific forces, for they would have torn it into fragments and scattered its remains far and wide throughout the planetary system.

Since the earth is dependent upon the sun for its light and heat and life, the source of the sun's energies is a question of the highest interest. It has radiated heat and light upon the earth at almost exactly its present rate throughout the hundreds of millions of years of the geologic ages, and an inquiring mind raises a question respecting the future. The source of the sun's heat is probably in the sub-atomic energies of the mass of which it is composed, and its radiation is probably in some way at the expense of its mass. Although the problem is now enveloped in uncertainties, it seems probable from several lines of evidence that the sun will continue to illuminate and heat the earth at approximately the present rate for many millions of years, even hundreds of millions of years, in the future. This possibility, of course, raises corresponding questions respecting the future of life upon our planet.

Not only have the distance, size, and mass of the sun been measured, but its chemical constitution has been determined. One cannot but wonder how such a remarkable thing has been done, an achievement that was said by philosophers less than a hundred years ago to be forever impossible. The basis of the method consists of the fact, established by laboratory experiments, that every element in a gaseous state radiates its own distinctive kinds of light, just as every kind of musical instrument gives forth its own peculiar tones. The spectroscope is a marvelous instrument that separates light into its constituent parts and enables the astronomer to determine whether or not those rays, for example, which iron radiates are being received. By this means it has been found beyond a shadow of a doubt that the sun contains in enormous quantities such familiar elements as hydrogen, helium, carbon, oxygen, sodium, calcium, iron, nickel, copper, and zinc—

in fact, nearly all the metals known on the earth except a few of the heaviest ones. The same method can be applied, also, to the determination of the constitutions of stars that are millions of times as distant as the sun, and in many cases they are found to be almost exactly like the sun.

7. **The stars.**—One of the most inspiring sights on which the human eye ever rests is the vault of the heavens on a clear, moonless night. The whole dome appears to be covered with tiny points of light—jewels on a crystalline sphere, as the ancients thought of them. They form many curious outlines—the Big Dipper in Ursa Major, the semicircle in Corona Borealis, the diamond in Delphinus, the cross in Cygnus, etc.—and mythology is rich in stories respecting them, yet the actual facts are enormously more interesting than any romances that were ever woven about them.

The stars are suns, often much greater than our own. The ruddy Betelgeuze, in Orion, visible in the southern sky during the winter months, was found by Professor Michelson to be in volume 27,000,000 times as great as our own sun, itself 1,000,000 times larger than the earth. Red Antares, visible in the south during the summer, is even larger. The red stars are tenuous bodies, their average densities being below that of our atmosphere at the surface of the earth. Many stars, such as the Pleiades, the white star Rigel, in Orion, and the far southern Canopus, in Carina, emit hundreds or even thousands of times as much radiant energy as our own sun.

Besides the stars visible to the unaided eye, 5,000 in number, there are hundreds of millions of fainter and more distant ones that can be seen only with telescopes. A long-exposure photograph of nearly any part of the sky shows thousands of stars, even though not one may be visible without optical aid, and in the Milky Way they cover the plate with thousands of minute images.

When one looks at such a photograph as that reproduced in Figure 9, he gets the impression, perhaps subconsciously, that the stars at least in that part of space are near one another. But things are not what they seem. The unit of space commonly used

by astronomers is a sphere whose radius is, in round numbers, 200,000 times 100,000,000 miles, and even where the stars appear to be as numerous as in Figure 9 there is only 1 star, on the average, to 5 or 10 of these vast units. If a sphere having a radius of 200,000 times 100,000,000 miles were constructed with its center at the earth, it would contain within its interior no star except our own sun.

The distances of the stars are not given in miles, for the numbers corresponding to such a unit are so large they cease to have any meaning to our minds. Instead, the distance light travels in a year is frequently taken as the unit. Light travels 186,000 miles per second, as far as 7 times around the earth during a heart beat, or from the moon to the earth in a second and a quarter. A light-year is, therefore, in round numbers 6,000,000,000,000 miles. The nearest known star, Alpha Centauri, below the southern horizon, is distant about 4 light-years, and great Sirius, the nearest star visible in northern latitudes, is distant about 8 light-years. Compare with these near neighbors the North Star at 40 light-years, the Big Dipper at 70 light-years, and the Pleiades at 300 light-years. At the distance of even the nearest star a planet as great and as intensely lighted as Jupiter would be invisible if our telescopes were 1,000 times more powerful than the greatest ones so far made. Consequently there is no direct evidence, and possibly there never will be any, that those distant suns which we call stars have or do not have planets revolving about them. Although a planet at the distance of a star would be invisible, it has been found that many a star, perhaps one in five, is in reality a double sun, the two components revolving about each other usually at a distance of many, even hundreds, of millions of miles. Each of these twin suns might be separately accompanied by planets, or distant planets might revolve about the pair.

The stars are called "fixed stars" because, in contrast with the planets, they preserve the same relations to one another during the brief periods of human history. When the Egyptians were building the pyramids the constellations circled above them al-

most exactly as they are seen today. But the stars are not exactly fixed. Refined observations with telescopes show that they are moving across the lines joining the earth to them, and observations of another kind with spectroscopes prove that they have relative velocities toward or from the solar system. The relative motions of the stars with respect to one another are at the rate of about 600,000,000 miles per year. As observed with the unaided eye, they are apparently fixed for long periods because their distances from the solar system are so great that a motion of 600,000,000 miles per year for 1,000 years is not appreciable. But in the course of geologic time they will pass and mingle differently, and the whole aspect of the sky as seen from the earth will change. The stars do not move about some great center, or in simple closed curves like the orbits of the planets, but more or less irregularly like bees in a swarm. It is true, of course, that during the brief interval they have been observed they have moved in straight lines. The irregular character of their paths when followed for millions of years is inferred from their distribution and the forces to which they are subject.

The stars are of four principal types, the classification depending upon the kinds of light they radiate as determined by the spectroscope. These classes may be different kinds of stars, or different stages in the evolution of stars of fundamentally the same kind. The first type are great white or bluish-white suns, usually much larger and more brilliant than our own, having surface temperatures ranging from 20,000° to 30,000° Fahrenheit, and radiating light from hydrogen and helium. Nearly half of all stars are of this type. Stars of the second type are yellowish, our sun being an example. About half of all the stars belong to this class. The two remaining types are red stars of lower temperatures which contain many elements and also compounds in their atmospheres. These two types are made up of relatively few examples.

It has usually been assumed that the white stars are young suns, using the word young in an astronomical sense, that the yellow stars are farther advanced in evolution, and that the red

stars are old suns nearing extinction. The duration of suns is so great, certainly thousands of millions of years, that the problem of their evolution is naturally one of great difficulty for creatures whose lives individually, and whose civilizations even, last only a moment of geological time. But insatiable curiosity drives us to attack again and again even so transcendental a problem, and although for the time we may be enveloped in the fogs of uncertainty, we are confident of ultimate success in our attempts to solve it.

8. Globular star clusters.—The celestial spaces are occupied not only by individual and double suns, but also by other cosmic masses and groups. There are, for example, diffuse nebulous masses of such great extent that in some cases hundreds of years are required for light to cross them. There has been a widespread opinion among astronomers that these nebulae will eventually condense into suns. If this is the course of their development, the time required for the evolution will be so great that compared to it the geological ages will be negligible.

Among the most interesting cosmic groups are the globular star clusters. They consist of immense spherical aggregations of suns, ranging in number from a few thousands up to one hundred thousand.

Every one of the larger stars shown in Figure 10 radiates a thousand times as much light as that given out by our sun, yet they are so remote that the entire cluster, appearing like a faint, fuzzy star, is on the very limits of visibility with the unaided eye and the other clusters can be seen only through a telescope.

The photograph gives the impression that at least in the center of the cluster the stars are crowded closely together, so closely, in fact, that they must frequently collide, and so closely that it would be impossible for planets to revolve about them. Again things are not as they appear to be. The cluster is distant 20,000 or 30,000 light-years, and the space occupied by it is so vast that several hundred years are required for light to cross it. Perhaps its perfectly astounding character is best indicated by

the fact that the average distance between adjacent suns, even in the very heart of the cluster, is something like 100,000 times the distance from the earth to the sun. Not only will the stars of the cluster not frequently collide with one another, but there is abundant room for planets to revolve about them in families much greater than that belonging to our own sun. How greatly fact often transcends fancy! Before modern science enabled men by their instruments and by their reasoning powers to go out beyond this tiny planet upon which we live and to wing their way securely through the celestial regions, no scientist, nor philosopher, nor poet, nor theologian ever dreamed in the wildest flights of his imagination that the whole physical universe is so great in volume, in mass, in energies, and in possibilities of evolution and life as the single cosmic unit whose photograph is reproduced in Figure 10. In *Paradise Lost*, written less than 300 years ago, Milton drew the most graphic and magnificent picture of the universe ever created by man; and although he made use of all the science of his day to stimulate his unrestrained imagination, his Cosmos compares with these aggregations of stars as a drop of spray compares with the ocean.

The rocks of mountains are broken up by air and water, and their disintegrated remains are carried away by rivers to the sea. The earth as a whole, the other planets, and the sun are in a ceaseless state of change. So, too, are the globular clusters. But the scale of these groups of stars is so great in space and in time that actual motions have not been noted in the few decades during which they have been observed. It can be shown from their distances, dimensions, and the number of stars they contain that no observable displacements of the stars with respect to one another can be expected inside of a hundred years.

The stars in a globular cluster circulate about among one another like bees in a swarm. Each one moves subject to the gravitation of all of the remainder, and its motion is much as though the mass of the remainder were scattered uniformly throughout the volume occupied by all of them except when, oc-

casionally, it passes near another star, say within a distance a hundred times that from the sun to the earth. At such times its motion is greatly modified, much as the motion of a molecule is abruptly changed when it encounters another molecule. In fact, the dynamics of globular clusters has been compared to the dynamics of a gas. Molecules moving in our atmosphere at the speed of 1,500 feet per second meet and rebound from other molecules 250,000 times in going an inch. More than a million years are required for a single circuit of a star into the interior of a globular cluster and out again; and the distances between the stars are so great that on the average a star approaches another star only once in thousands of circuits.

The beautifully symmetrical forms of the globular clusters, most of them having essentially the same structure, is evidence that cannot be doubted that they have existed long enough as cosmic units for all irregularities of distribution to be worked out by a dynamical evolution. In such an evolution the near approaches of stars are major events, and since for a given star they happen only once in thousands of millions of years, it follows from the forms of clusters that they have existed as independent systems for thousands of millions of years. These results are obtained by the methods that seem as safe as those by which the geologists infer the great age of the earth from the strata of the rocks and the salinity of the ocean, and those best qualified to judge do not doubt the correctness of the conclusions.

9. **The galaxy.**—The hundreds of millions of stars within the reach of modern telescopes do not form a chaotic mass; nor do they extend uniformly to infinite distances. They occupy, rather, a disklike, or watch-shaped, figure in space, whose thickness is about one-tenth or one-fifteenth its greatest diameter. The shortest distance through this galaxy of suns, that is, the distance from the face to the back of the watch-shaped figure, is probably 10,000 or 20,000 light-years, and the equatorial diameter is probably more nearly 100,000 light-years. These numbers are subject

to considerable uncertainty, but there are good reasons for believing that they are of the right order of magnitude.

The number of stars in our galaxy is certainly as great as 1,000,000,000 and possibly there are twice this number. The uncertainty lies chiefly in the fact that the less luminous and dark stars are not visible with present instruments at a distance of tens of thousands of light-years. It is reasonably certain, however, from dynamical considerations, that the total mass of invisible stars is not in excess of the mass of visible stars.

The galaxy is not a homogeneous mass of stars, but it is composed of great clouds of suns, thousands of light-years across, of dense globular clusters, hundreds of light-years in diameter, of immense open clusters, of many types of nebulae, and of individual and multiple stars. Our sun is deep within the galaxy, yet thousands of light-years from its center. When a person looks out in the plane of the galaxy the numerous stars in the line of his vision make up the Milky Way; when he looks at right angles to this plane, the stars are apparently much less numerous. The sun is moving about 400,000,000 miles per year with respect to the stars that are now in its part of the galaxy. The direction of the sun's motion is toward a point in the constellation Hercules, which is a little southwest of the zenith on October first at eight o'clock in the evening. The average for all the stars whose velocities have been determined is about 600,000,000 miles per year. Although stars are found moving in every direction, there are many great groups, such as the Pleiades, the Hyades, and the Big Dipper, which drift through space in sensibly parallel lines with equal velocities, and there are two opposite directions in which there is a tendency for all the nearer stars to stream.

When considered as a whole, the galaxy is seen to be a vast cosmic unit whose dynamical evolution has not yet proceeded to the steady state that is found in the globular clusters. Its great swarms of stars will surge and mingle throughout periods of time counted in millions of millions of years. This immense circulation

of suns, roughly analogous to an irregular distribution of various kinds of molecules in a gas, will tend more and more toward a symmetrical oblate form with stars uniformly distributed in concentric layers. While this dynamical evolution is in progress the sun will make wide excursions in the galactic empire, now winding its way for hundreds of millions of years through the thickly populated deep interior, and then approaching for a time the shores of the empty regions beyond, only to be pulled back by the gravitation of millions of suns before it drifts forever away into the night of space.

In its wanderings through the galaxy, the sun, and every other star similarly, runs the chance of having important adventures. Occasionally it will pass near another sun, perhaps within the radius of the orbit of the earth, or perhaps within a distance a hundred times as great. When two great masses, highly heated and spouting up flames hundreds of thousands of miles, approach each other, it seems highly probable that each will stimulate more violent activities in the other. Then something resembling a spiral nebula, though on a much smaller scale, will be developed, and it will evolve gradually into a family of planets. If a sun already has a family of planets at the time of its near approach to another star, they will almost certainly be broken up and destroyed, their fragments mingling with the débris out of which a new family will develop. The new planets, in turn, will endure until their sun again passes near another star.

The foregoing statements not only roughly outline (the outline will be completed in the next chapter) the origin of the earth and the other planets now revolving about our sun, but they prophesy their destruction. The average period between the birth and destruction of planets, the period during which they grow and evolve and, in some cases, support life that, too, evolves, is one that can be roughly determined. It follows from the volume of the galaxy, the number of stars it contains, and their average velocity, that on the average for many successive near approaches, the period is of the order 1,000,000,000,000,000 years. During an

vast an interval, which is a rough measure of the possible lifetime of a family of planets, a star will many times traverse the galaxy. During these excursions it will probably lose mass by radiation, and sometimes gain mass for perhaps a million years by passing through a nebulous or meteoric cloud; it will possibly sometimes fade away and become obscure; and one of its planets may grow into a companion sun. The hundreds of millions of stars that now blaze in glory in the sky, and the absence of a comparable number of obscure ones, are our warrant for the belief that suns live on and on through many life-cycles of planets, if not forever.

10. **Exterior galaxies.**—Having measured and weighed the earth, explored the solar system and discovered the laws of motion of its members, determined the chemical constitution of the sun and the stars, and marked out the far limits of our galaxy, all within 300 years, astronomers are now reaching out beyond our family of suns to distant galaxies. For several decades curious objects, called spiral nebulae, have been observed apparently among the stars, but possibly outside and far beyond them. Most astronomers have recoiled from the thought that they might be distant galaxies, for the average human mind is terrified by great distances and long intervals of time, and usually accepts them as possible realities only long after abundant evidence has made necessary the step. In this case the positive evidence is only now (in late 1924 and in 1925) at hand, and it proves that what has been called the Andromeda nebula, instead of being a vast mass of gas lying out among our stars, is in reality a distant galaxy, so distant that 1,000,000 years are required for its light to come to us, a galaxy similar to our own in shape and size and composed of a comparable number of suns. The corresponding results have been established for a few other exterior galaxies. The astonishing fact is not that they are so far away, but that they are so near that their distances can be approximately measured.

There are hundreds of thousands of spiral nebulae, ranging from such great objects as that which is seen through the stars

in Andromeda down to those at the limits of the greatest telescopes. It is probable that they are all exterior galaxies, some comparable to our galaxy, some greater, and some smaller. At this point observational evidence ceases, and at this point, too, we may cease to consider the question; or, if we prefer, we may formulate tentative hypotheses, guided, of course, by analogies with the known, and examine their consequences.

A long series of physical units, each made up of smaller ones, has been established. The smallest particles of matter now known are the electrons which are the constituent units of which atoms are composed. In a different way, a few or many atoms are joined into molecules. Molecules are the units in the structure of the myriads of compounds that make up worlds. Worlds and the sun are components of the solar system, and hundreds of millions of suns constitute the galaxy. Now it is found that there are exterior galaxies in enormous numbers. Do order and structure terminate here? If analogy is any guide and if the intuition is not wholly misleading, the answer is, "No!" In spite of the very important differences in the steps from one to the next of the several classes of units that have been enumerated, it seems to be a reasonable hypothesis that many galaxies, perhaps millions, are the constituent parts of a super-galaxy. Then the question arises whether or not there are other super-galaxies, and the affirmative answer seems more probable than the opposite. The mind shrinks from the conclusion that there is not order here, and consequently it postulates, tentatively, that many super-galaxies of the first order constitute a super-galaxy of the second order, and so on in an unending sequence. If this is substantially correct, the physical universe is infinite in the sense that it extends through infinite space, and that there are not only infinitely many suns, but infinitely many galaxies and super-galaxies of every order.

The foregoing is frankly speculative, but it should not be condemned for that reason, for it is found upon consideration that every attempt man has made to place himself in the Cosmos is involved in speculations. It ought to be regarded, rather, as a tenta-

tive outline of the physical universe which should be compared with observational evidence and whose implications should be considered. According to this hypothesis the universe has no center and the earth occupies no special spot that is not paralleled by other worlds an infinite number of times. If the physical universe were finite, so far as science can now determine, its energies would be dissipated into space and it would tend toward a condition of eternal darkness and death. But in an infinite universe no such melancholy conclusion would be in prospect, for even if energies once radiated away were never integrated again, still there might well be, and probably would be, transformations of matter by energy throughout infinite time.

11. Concluding reflections.—The reactions to a brief sketch, such as the foregoing, of the astronomical aspects of the physical universe vary greatly from one person to another. An experienced scientist is deeply conscious of its incompleteness with respect to facts, he is almost offended at its dogmatic tone, and he regrets that it gives no just impression of the enormous toil that the achievements of science have cost. But the inexperienced have no such thoughts, for they are like a debutante at her first party, entranced by the bright lights and wholly unconscious of the fact that they might be traced back through transmission lines and power plants and train loads of coal to a miner who, with bent back, wields his pick in a dark and damp subterranean cavern. The sophisticated scientist is partly wrong in his feeling of personal affront and in his regrets, for in order to make progress the world must accept without the details of proofs, or without appreciating what they cost, most of the results obtained by our predecessors, and by our contemporaries as well. But the scientist is wholly right when he maintains that the basis of all reliable knowledge is exhaustive investigation, and when he feels that only those who have penetrated deeply into at least one field of human endeavor can really have a profound reverence for truth or comprehend the cost of exploring the universe.

To those who for the first time have learned of the vastness of

our galaxy, to say nothing of galaxies beyond, the earth suddenly shrinks and human affairs seem to lose their relative importance. Often a temporary feeling of depression follows. This, however, is wholly unwarranted, for the existence of other worlds detracts nothing from this one nor reduces the complexity of the problems of an individual or of the race. On the contrary, the enormous extent and diversity of the universe and the remarkable success astronomers have had in exploring it increase our respect for the power and dignity of the human mind, and inspire high hopes for its future development.

To an astronomer the most remarkable and interesting thing about that part of the physical universe with which he has become acquainted is not its vast extent in space, nor the number and great masses of its stars, nor the violent forces that operate in the stars, nor the long periods of astronomical time, but that which holds him awestruck is the perfect orderliness of the universe and the majestic succession of the celestial phenomena. From the tiny satellites in the solar system to the globular clusters, the galaxy, and exterior galaxies there is no chaos, there is nothing haphazard, and there is nothing capricious. The orderliness of the universe is the supreme discovery in science; it is that which gives us hope that we shall be able to understand not only the exterior world but also our own bodies and our own minds.

SELECTED REFERENCES

1. F. R. Moulton, *Introduction to Astronomy* (The Macmillan Co.).
2. Herbert Dingle, *Modern Astrophysics* (The Macmillan Co., 1924).
3. Charles A. Young, *Manual of Astronomy* (Ginn and Co., 1923).

CHAPTER II

THE ORIGIN AND EARLY STAGES OF THE EARTH

ROLLIN T. CHAMBERLIN

Introduction.—To the people of antiquity man's abode, the earth, was the center of the universe. The sun-god drove a fiery chariot across the sky to illumine the earth by day, and at night the moon and the glittering stars passed slowly overhead to guide man on his way. But of man's many self-centered concepts, this simple picture was one of the first to be outgrown. Several centuries ago Copernicus reversed the viewpoint and taught the scientists of his day that our earth belongs to a system of planets revolving around the enormously greater sun. Though as important as ever to the human race, our earth was thus put into its proper place as a minor unit in the solar system and, as such, its birth, life, and destiny became accordingly incidents in the greater life-history of the solar system.

With the gradually widening circle of human knowledge, man's inquisitive nature led him to investigate this globe upon which he lives, to wonder how it came to be, and finally to speculate upon the interrelations of the sun and the family of planets to which it belongs. Just as the written life of some famous man properly commences with a portrayal of his family antecedents, so any real history of the earth should begin with the activities of the sun and the origin of its present family of planets. Naturally enough, many of the odd ways of the earth are direct inheritances dating from the birth of the solar system, and the nature of that birth becomes all important in any consideration of the growth and later development of the earth. Let us, therefore, try first to picture the origin of the solar system.

ORIGIN OF THE SOLAR SYSTEM

The foundation of science is a belief in the orderliness of the processes of Nature, and the firm conviction that these processes have operated in orderly fashion throughout the billions of years of the past. Guided by this belief, the geologist and the astronomer try to unravel the past development of the earth and the solar system in terms of the processes which are in operation today. The soundness of this method becomes evident when it is realized that within the system today there remain many vestiges, or inheritances, from bygone ages which, if carefully studied, will reveal the succession of past events.

We turn first to the sun. It is the largest body in the solar system and so is best fitted to be the parent, and it behaves as though it were the parent of the system. All of the planets circle around it and pay obeisance to it, as though they were its offspring. Let us assume that they are, and see how it works. But how came the planetary masses to be separated from the sun? What could project some of the sun's substance so far out as the planets now are? What keeps them out in their places, and what makes them revolve around the sun? These are too many questions at once. But using our method of considering what is going on now, we find plausible answers to these questions. In this quest for present processes which seem likely to suggest ways in which the planetary masses may have become detached from the sun, one does not have to look far. Good photographs of the sun, in many cases, reveal impressive fountains of matter spouting tens and even hundreds of thousands of miles above the solar surface. Some of these erupted masses are projected to heights of over 500,000 miles. From so many and so violent outbursts we know that the sun has great eruptive possibilities, and it is almost certain that it also had such possibilities during thousands of millions of years.

Ordinarily masses erupted from the sun fall back into it, because they are subject to no other force which rivals the sun's attraction. So far as this material returns to the sun, it, of

course, does not form permanent bodies outside the sun, such as planets. Some other competent force must have come into action in addition to the ordinary eruptive and repellent forces of the sun. Such a force must not only have given enough added energy to carry out larger masses than are now being erupted, and must have carried them out farther, but it must also have given them orbital motion so that they remained out at their several distances. Furthermore, it must also have been such a force as would be brought to bear only once in a long period of time, for the geologic record shows clearly that the formation of the earth dates back more than a billion years, and that during the recognized geologic ages the earth has not suffered serious interference from without. The planetary orbits show the same thing. If the planets of the solar system were formed at about the same time, we must look for a force which operated at the time of the origin of the planets, several billion years ago, but which has not operated in like fashion since.

Turning to the stellar galaxy, the hundreds of millions of suns traveling about in various directions at high velocities suggest definitely what that force was and how it operated. Owing to the vastness of the galaxy, the chances that any particular roving sun will actually collide with another sun are practically negligible, but the likelihood that it will come somewhere near another member of the stellar system is vastly greater. If, and when, another star does come close to our sun, the conditions which we have been seeking are met and the important event occurs. The gravitative pull of this passing star will operate against the gravitative attraction of our sun on its own mass in the line joining the two suns. Materials ejected from our sun will be drawn out farther by the pull of the visiting star, and in addition they will be given a cross-direction of movement by the other moving star. If the passing star is large and comes sufficiently close to the sun, the cross-motion which it imparts to these separate masses will prevent their returning to the sun, and will cause them instead to revolve around the sun in ellipse-like paths. This is the key to the origin of the solar system, according to the planetesimal hypothesis of

Chamberlin and Moulton.[1] Let us trace its workings in greater detail.

The birth of the family of planets.—Interpreting the past in terms of the present, we picture our sun, about as it is today, speeding onward in its endless journey through the stellar galaxy until after a long interval it comes into the vicinity of a similar traveling sun. When the other traveling sun is sufficiently close for its gravitative attraction to affect our sun strongly, it partially neutralizes our sun's gravitation along the line connecting the centers of the two bodies, thus pulling out a tidal bulge, or cone, toward itself and pulling the sun away from a similar bulge on the opposite side.

To understand this action better, think of the somewhat similar tides on the earth. There is a high tide on the side of the earth toward the moon, whose differential attraction draws the water in that direction. At the same time another high tide rises on the opposite side of the earth. This is because the moon's pull, which varies inversely as the square of the distance, affects the center of the earth more strongly than the far side. The earth is, in fact, pulled away from the water on the far side, which banks up there as a high tide.

This tidal action by a passing star combines with the eruptive forces of the sun to carry material out to great distances. With the help of Figure 12 let us follow carefully the behavior of such detached masses. In the first stage S_1 represents our sun and S'_1 the passing star, each moving in the paths indicated by the arrows. Mass a, expelled from the sun, is drawn out toward the passing star, while on the opposite side mass a' is left behind as the sun is pulled forward by the star.

In their flight past one another, S_1 moves onward to S_2, while S'_1 reaches the position S'_2. As the star moves toward S'_2, the direction of its pull on the detached mass, a, is constantly changing, and mass a acquires a cross-motion. Following the same prin-

[1] The planetesimal hypothesis was developed by T. C. Chamberlin and F. R. Moulton in 1900 and the following years.

ciple, S_2 is more strongly affected by S'_2 than is a', which lags behind relatively. New outbursts of matter from the sun are represented by b and b', directly toward S'_2 and also away from it.

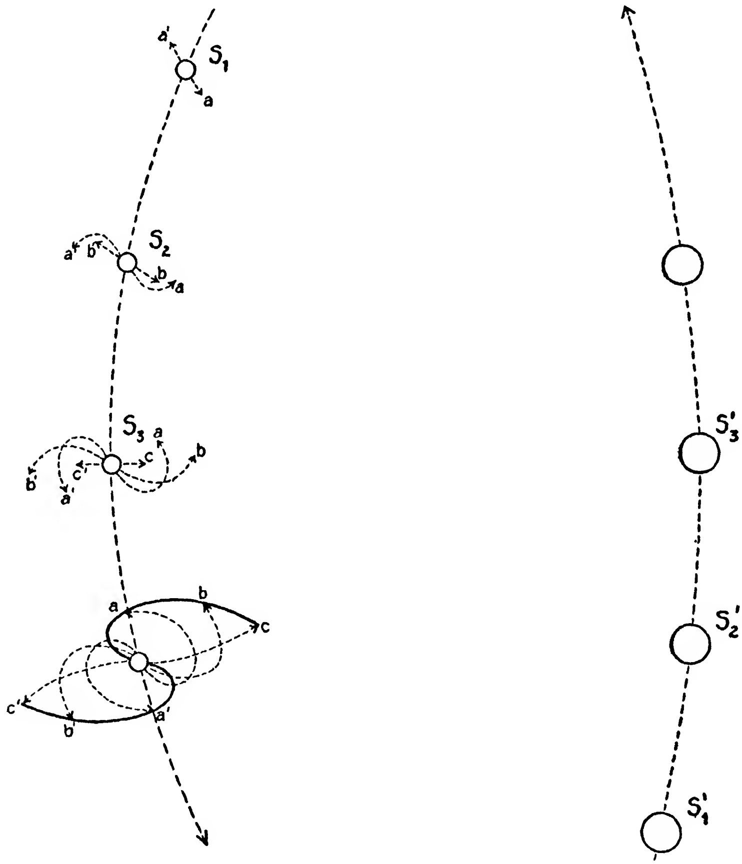


FIG. 12.—Formation of solar spiral by tidal action of a passing star upon our sun.

At a later stage the sun moves to S_3 and the star passes on to S'_3. Masses a and b are pulled still farther forward by the passing star, while a' and b' move correspondingly on the opposite side of S_3. New matter ejected from the sun is indicated by c and c'. If

another outburst should occur before the passing sun gets too far away to pull effectively it would produce two more such masses. In addition to the major outbursts, a streaming out of much scattered material contributes innumerable smaller bodies which behave much like the larger masses.

Our system dynamically like a spiral nebula.—Let us now take stock of the results of the visit of the passing star after its disturbing effects on our sun have quieted down. Most of the sun's material still remains in the central body, but extending outward on opposite sides are two curving arms composed of the scattered matter which has been ejected and given cross-motions. This gives the assemblage somewhat the appearance of a spiral nebula, such as have been revealed in large numbers by telescopes. But compared with the great, distant spirals, it would be very small indeed, and in various other respects the solar nebula, resulting from close approach, is quite different from these enormous spiral nebulae now being photographed.

Although the spiral nebulae that are now known to be giant systems at great distances can be used only roughly to picture the initial stages of our solar system, they have, nevertheless, played an important part in illustrating the planetesimal hypothesis, which we are following. The striking photographs of spiral nebulae nearly all show large, dense patches of matter spaced at intervals along the two curving arms. Smaller knots of matter are scattered throughout the arms, but many of them are close to the larger knots. In addition, immense numbers of still smaller objects make up the general haze.

This picture becomes a suggestive guide for the further investigation of our sun, tidally disrupted by the passing star. Masses *a*, *b*, and *c*, in Figure 12, constitute large knots of matter resulting from successive major outbursts from the sun. Lesser outbursts produce smaller knots of matter, some of them sufficiently near the larger ones to be controlled by their gravitative attraction, while others, farther away from the main masses,

remain free from the control of the large knots. In addition, much smaller particles are scattered about in great numbers. This entire assemblage of sun, knots (large and small), and fine, scattered particles, constitutes the parent of our solar system.

The solar spiral becomes the solar system.—As a consequence of the new motion imparted by the passing star, all of the knots and smaller particles are left moving in orbits of revolution around the sun, which constitutes the center of the system. Such orbits are not circles, but mostly elongated ellipses of quite various eccentricities. Each separate mass is now destined to continue in its elliptical orbit around the sun until interfered with by some other body, or some outside force. It is governed in its course by the balance between the centrifugal acceleration due to its speed of revolution and the pull of the central sun. If all of the orbits were nearly circular, only a few of the separate bodies moving in them would come into collision with one another. But since the orbits are ellipses differing much in shape and dimensions, many of the particles have opportunities of collision. Figure 13 portrays two bodies moving in intersecting elliptical orbits around the sun. Suppose that one of them is a large body, like one of the main knots, while the other is one of the many small particles. After many circuits around the sun, the time will come when these two bodies will collide at one of the intersections of their orbits. When this occurs, the larger body gathers in the smaller one and adds it to its own mass. Thus the larger body grows. As the hypothesis postulates vast numbers of tiny particles in crossing orbits, the

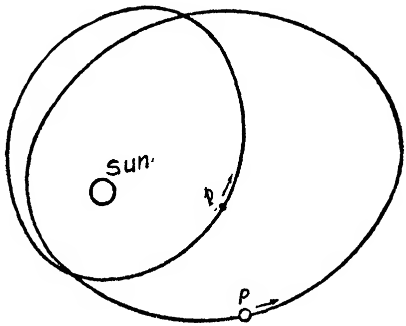


FIG. 13.—Two bodies moving in elliptical orbits around the sun. *P* represents planetary nucleus, *p* a planetesimal.

few large bodies will, in the course of a long period of time, gather into themselves most of the scattered material and grow greatly in size.

The larger knots of matter, represented by *a*, *b*, and *c* and *a′*, *b′*, and *c′*, as they grow, become the planets. The somewhat smaller knots of matter close enough to the planetary knots to be controlled by their gravitative attraction, as they grow in similar fashion, become the satellites of the planets about which they revolve. Other small knots, beyond the dominating control of the planetary knots, grow to become the planetoids of our present system. The myriad of scattered tiny particles which constitute the food for the growing planets and their satellites are consumed in the process of growth and largely disappear. These tiny bodies are called planetesimals (very minute planets), and the hypothesis takes its name from them since the theory is fundamentally one of growth of the larger bodies by the gathering in of planetesimals (Figure 14).

As each of the planets sweeps up the planetesimals from its neighborhood, not only does it increase in mass, but at the same time its orbit is correspondingly modified. The averaging of the many ellipses described by the planetesimals eliminates the individual irregularities and brings the combination nearer and nearer to a circle. We should, therefore, expect to find that the larger planets, which have gathered in the most planetesimals and thus have combined the largest number of different orbits, are now following the most nearly circular pathways around the sun. Such is strikingly the case in the solar system today. The great planets, Jupiter, Saturn, Uranus, and Neptune, have more nearly circular orbits than have Mars and Mercury, the smallest planets, while the much smaller planetoids, which have grown but slightly, have the most eccentric orbits of all.

Not only do the planets revolve around the sun as a result of the visit of the passing star, but they also rotate upon their axes. To some extent the planetary masses were whirling as they left the sun, but the impacts of infalling planetesimals have

greatly modified any original spin which they possessed. Each collision is likely to affect the rate of spin, and the majority of impacts and the balance of momentum determines whether the planet has forward spin or backward spin. A relatively simple

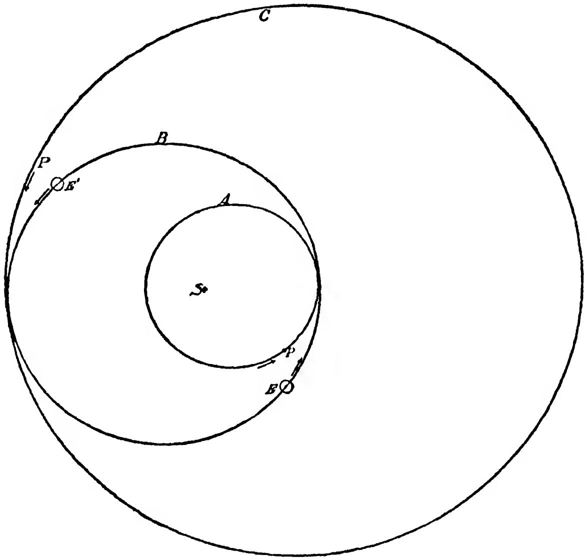


FIG. 14.—Diagram illustrating the condition under which collisions may take place in elliptical orbits of the planetary type. S represents the solar mass at the center of the system, E the planetary nucleus, B its orbit, P a planetesimal in orbit C, larger than B, and P a planetesimal in orbit A, smaller than B. The case has been so chosen as to represent at once the smallest and the largest orbits of typical eccentricity that can come into contact with the orbit of the planetary nucleus. (From T. C. Chamberlin, *The Origin of the Earth.* University of Chicago Press, 1916.)

diagram has been used in textbooks to show that the majority of impacts will tend to produce rotation in the same direction in which the planet revolves around the sun, which is known as forward rotation. But backward rotation is possible in certain cases. In harmony with this view, the Earth, Mars, Jupiter, and Saturn rotate in the forward direction and the majority of their satellites have forward revolution, while Uranus rotates in the retro-

grade direction. The directions of rotation of Mercury, Venus, and Neptune are uncertain. Of the numerous satellites of the system, all but two of Jupiter's nine moons and one of Saturn's revolve around their primaries in the forward direction. The three black sheep of the flock are, however, explained by our theory.

As people are more concerned about our planet than with the other members of the planetary family, let us now consider the rôle which the earth has played in this drama. We can imagine it born of the sun, occupying a field of its own in the planetary domain, growing on a steady supply of planetesimals, gradually acquiring a more nearly circular course around the sun, and developing its rotation until it now has a day of twenty-four hours. In the meantime its fellow-traveler, the moon, a small companion body since the birth of the earth, has been subject to its control, has whirled round it in response to its gravitative commands, but has never rivaled it in size. The growth of the earth is now nearly complete. The brilliant shooting stars, which are seen to streak the sky on a clear night, do add slightly to its mass, to be sure, but their additions are unimportant.

The features of the earth and of the rest of the solar system have led to, and are seemingly explained by, the planetesimal hypothesis, but it is a poor hypothesis which will not explain the things for which it was intended. So much is presupposed. The real test comes later when other things, unknown when the hypothesis was launched, come to be discovered—whether the new facts have to be twisted and the hypothesis modified to make them fit, or whether, on the contrary, they fit in easily and lead on like a Sherlock Holmes clue, to further developments of the theory itself. As yet, the planetesimal hypothesis is not very old, but since its appearance a few new discoveries have been made which should tend further to make or mar it. Such are the discoveries of the three retrograde satellites, the discovery of radium and radioactive substances in the earth, and the development of our present understanding of volcanoes and the processes on which they are dependent. A detailed discussion would show

Fig. 9.—Photograph by Barnard at the Yerkes Observatory of star-clouds in the Milky Way.

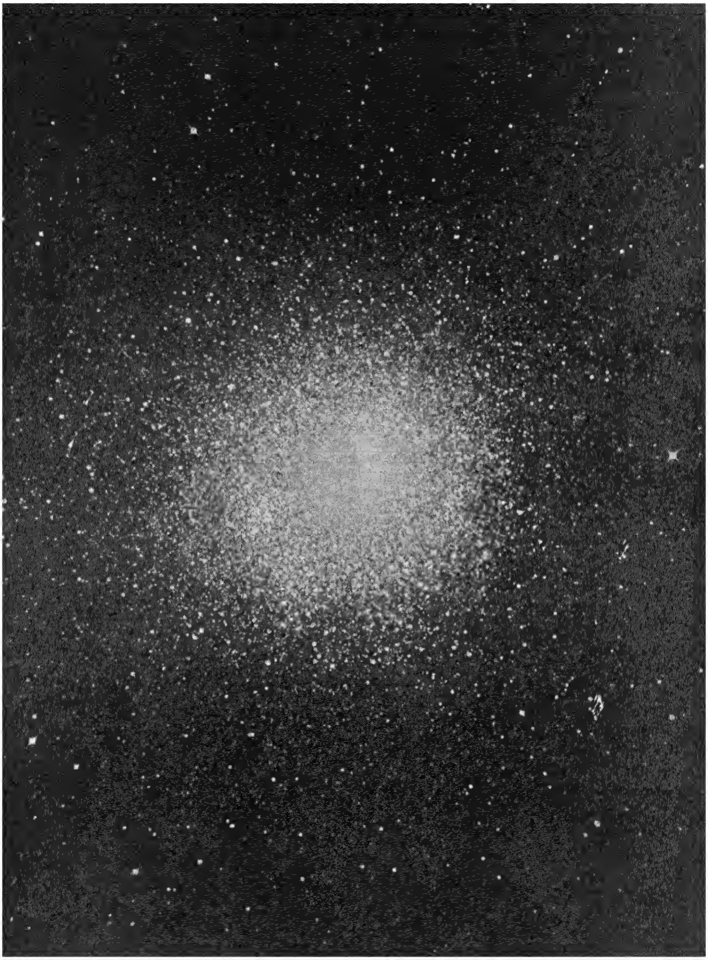


FIG. 10.—Photograph of 100,000 suns in the Great Hercules star cluster \ the 100-inch reflector of the Mount Wilson Observatory.

that these new additions to knowledge are in harmony with and strengthen the hypothesis which we have been following.

The Laplacian hypothesis.—The conception which we have been following is one of the developments of the twentieth century. Throughout the nineteenth century the nebular hypothesis, launched by the French mathematician, Laplace, held almost universal sway and was confidently believed to be the true story of the development of the solar system. Laplace naturally enough did not go back to the beginning of things but, as a starting-point, supposed the matter of the present solar system to be a mass of hot gas, spheroidal in shape and rotating. As the gas gradually cooled, it shrank and consequently whirled faster and faster. With increasing speed, at various stages rings of gas were left behind in its equatorial region. A ring was assumed for each of the planets. After the last ring was formed, the remaining material by further contraction, became the sun. Each ring of gas after being formed came together as a rotating spheroid. Just like the main mass, these spheroids cooled, shrank, rotated faster, and detached secondary rings which, in turn, later condensed into the satellites of the planets. In this very regular and simple manner the solar system was supposed to have developed into its present form.

Each ring, large or small, and every resulting planet and satellite must, if formed thus, both revolve and rotate in the same direction, and so far as was known until recently, they all did. Since the Laplacian conception was very regular and beautifully harmonious, scientists believed that it must necessarily be true, and it had furthermore the prestige of the great name of Laplace behind it. It used to be said that if a single satellite of any one of the planets moved in the direction opposite to that of the others, that alone would be sufficient to wreck the hypothesis; but not one did. Therefore it was a wonderful hypothesis and must perforce be true. Geology was based confidently upon it. For a hundred years it was not seriously questioned, but more recently, many difficulties of a very grave nature have been brought to light. Let us briefly look into some of these in order to understand why

this time-honored theory, which has played such an important part in the development of the earth sciences, has finally had to be abandoned.

Why the Laplacian hypothesis has been abandoned.—In the first place, the supposed rings are at variance with what has been learned of the behavior of gases. Instead of a whole assemblage of gaseous molecules all waiting for the given signal to come off together in the form of a ring, the molecules would be certain to depart one by one. They would scatter and a ring never could form. Particularly the lighter and more actively moving molecules, like hydrogen and water vapor, would escape, and hence not remain to produce the water now so abundant on the earth. Furthermore, it has been shown that a very attenuated gaseous ring of the sort required by the hypothesis, even if it could form, could never come together as a spheroid, nor could it continue as a gas sufficiently long to detach secondary rings to make moons for the planets.

One of the basic principles of any system free from outside forces is that the quantity of rotation (technically called moment of momentum) remains the same throughout its various stages. Hence, as each gaseous sphere shrank, detached rings, and still further shrank, it must have rotated faster and faster. All the planets should turn completely around in less time than their moons circle about them, and the sun should be whirling at a very high rate of speed. But gaze at our neighboring planet Mars through a large telescope and note that its fast-traveling moon, Phobos, makes three full journeys around Mars while the latter is turning once. According to the Laplacian hypothesis it should be the other way; Phobos should require more than a Martian day to make one of its journeys. Furthermore, Saturn's beautiful inner ring whirls around in less than a Saturnian day; and the sun, which should be rotating at the terrific speed of 270 miles per second, turns leisurely at 1¼ miles per second.

Suppose that we give to the original rotating mass of gas postulated by Laplace the present quantity of rotation of the solar

system (which it must have had if the hypothesis is good for anything). Then a computation shows that it would need to contract to well within the orbit of the innermost planet before it would be going fast enough to detach a ring at all. Hence the planets could not be where they are. In addition, the inclination of the sun's axis, the eccentric orbits of the planetoids, the unexpected discovery of three retrograde satellites, and other facts are adverse to the hypothesis. It follows that this long-held theory, so regular and so harmonious within itself, but running counter to the facts, can no longer be maintained and must be abandoned.

Very recently modifications of the planetesimal hypothesis have been published by Jeans and Jeffreys in England. They neglect the eruptivity of the sun and attribute more to tidal disruption, but these modifications seem less satisfactory than the original form of the hypothesis, which we have been following.

THE YOUTHFUL STAGES OF THE EARTH

Though happening long ago, the doings of the youthful earth do not form a chapter lost in the obscure past. An orderly youth, it followed closely certain prescribed rules of conduct; there are no escapades of its own to be recorded. These rules of conduct are within our grasp, but everything depends upon what kind of an earth it was at the start. According to the Laplacian hypothesis, it was a hot, gaseous, and later liquid earth; according to the planetesimal hypothesis, it was a solid earth. The plot works out very differently depending upon the opening scene.

The molten-globe story.—As the followers of Laplace wrote the story, the whirling mass of hot gas cooled to a liquid, though still very hot like slag in a blast furnace, and then froze over on the surface, giving the earth a solid crust. While the temperature was high, all the water of the globe, now in the oceans, lakes, rivers, soils, and living tissues, was in the atmosphere as a vast envelope of steam. Likewise the carbon now locked up in the extensive limestone and other carbonate deposits, that in the

coal beds, together with that in existing plants and animals, was also in the atmosphere in the form of carbon dioxide. Mixed with it were the gases of our present atmosphere. The water vapor alone would have amounted to 200 times our present atmosphere, while the carbon dioxide would have been 50 times our total atmosphere today. Later, as the earth cooled further, the water vapor gradually condensed from the atmosphere, forming the oceans, and rivers began to flow from the lands. Sands and muds laid down in the ocean, later hardening to sandstone and shale, started the first sedimentary rocks resting on the original crust. And finally, when the temperature permitted, life appeared.

With such a vast quantity of carbon dioxide and abundant water vapor in the atmosphere, the early climates were naturally supposed to have been very hot and moist. Gradually the atmosphere dwindled, and the climate cooled to its present condition. It is just about right today, but what is in store for the future? To answer this question, the older geologists drew a clear-cut picture, but it was painted in gloomy colors. They said: The earth once had 250 atmospheres; now it has only one atmosphere, already it has lost 249 atmospheres and it will soon lose the rest, and all life on the globe will die. They pointed to the moon, a much smaller body, and hence one which has gone through these stages more rapidly, as a prophecy of what will happen to the earth. As the dead moon is now, so a dead earth may be expected in the near future: a dismal prospect, but that is only half of it. The climate was formerly very hot, now it is comfortable, but soon it will become very cold. They pointed sadly to the glacial period from which the earth has rather recently emerged, a time when glaciers came from the north and reached as far south as Kentucky. This was the first frost of the oncoming winter. Now we are enjoying a brief spell of Indian summer; but the final freeze-up is not far distant. Thus they described the last inhabitants of the earth, gasping for breath and dying from the all-pervading cold.

What do the recent discoveries in the field of geology lead us to think of this story? In the first place, if the full-grown earth

had been in a hot, liquid state, it would have taken a smooth, globular form, modified by rotation, and there would be no reasonable explanation why the great continents should stand forth as they do, or why the great ocean basins should sink so deep below the sea surface. Without high-standing continental platforms, a universal ocean would have covered the surface of the globe; there would have been no land-life and man would not have come into being.

In the second place, we should find the original granite crust which formed as the earth solidified. Large areas of granite rocks in Canada, the British Isles, Brazil, Australia, and elsewhere were once pointed out as this primary crust. Now a closer examination shows that these granites are not the oldest rocks, but were injected, while molten, into still older rocks which were laid down as sands and muds in the oceans. Geologists today do not know of any rocks which can be interpreted as an original crust.

If the early climates were very hot and moist and the earth was enveloped in a dense cloud-filled atmosphere, the rock formations made in those times and the fossil relics of the plants and animals which lived in those ages should even today give consistent evidence of these conditions. If the early climates were very hot, no deposits made by glaciers should be found among the early rocks. If the early climates were very moist, bedded deposits of salt and gypsum, such as are produced only by the drying up of seas, lagoons, and lakes, should not be found in the rock layers made in those times.

But what is actually found? Willis and Blackwelder, floating down the Yang-tze Kiang in a native Chinese houseboat in 1904, one day toward sundown, tied up for the night in the midst of one of the stupendous gorges through which this mighty river wends its way. Close to the point at which they pitched their camp they unexpectedly discovered a very ancient glacial formation more than a hundred feet thick. Stones scratched as only glaciers can scratch them told unmistakably of a glacier which covered this region very early in geologic history. This locality is in about the same latitude as New Orleans, and today one can

enjoy swimming in the river there in March. Other glacial deposits, formed at the same time as those in China, are now recognized in portions of Australia where tennis is played out of doors all the year round. So we know that early climates were not always hot; at times they were even colder than they are in the same regions today. In the same way, deposits of salt and gypsum in ancient layers of rock tell us that the regions in which they are found experienced dry climates in the very remote past.

Plants and animals, whose fossils are now found in the rocks, also caution us not to believe this molten-globe story. These old plants and animals were fitted to live in climates which were sometimes like those of today, sometimes warmer, sometimes cooler. They indicate that living conditions on this globe were possible even near the dawn of geologic history, and that there has been no progressive cooling off and drying up of our earth. Instead of one great swing of the pendulum from very hot and moist climates to very cold and dry, there have been a great many lesser swings. Thus the direct evidences from the rocks and the testimony of life tell us not to worry about a dismal future prophesied for our earth on the molten-globe hypothesis. It is not the true philosophy. Hence we leave the molten-globe story, and in its place follow one which seems more closely in accord with the facts, and which, incidentally, has a happier outcome.

The story of the slow, solid growth of the earth.—In accordance with the planetesimal hypothesis, the earth began its career, separate from the sun, as a comparatively small mass. This small, original mass constituted the core of the earth-to-be. Just how large it probably was, we cannot say. Perhaps it amounted to about one-tenth of the present mass of the earth, possibly it was larger. From these beginnings it has grown to its present size by the infall of planetesimals.

Beginning of the atmosphere.—Whether or not this original earth-knot was surrounded by an atmosphere at the start depended chiefly upon its mass. The moon has no atmosphere because the gravitative force of such a small body cannot hold

gases around it. Mars, whose mass is about one-tenth that of the earth, possesses a thin atmosphere. The giant planet Jupiter holds an enormous atmosphere. The amount of atmosphere surrounding any planet is just what its gravity can hold, another argument against the vast atmosphere called for by the molten-globe theory. If the earth-nucleus amounted to one-tenth of the present earth, it quickly acquired a thin atmosphere, comparable to that surrounding Mars today. We can be sure of this because atmospheric gases would be supplied from several sources. In the first place, not all planetesimals were solid particles; many of them were probably individual molecules of gas. These would form an atmosphere directly. In the second place we find that meteorites, when heated, give off various gases, amounting to several times their own volume. If the meteorites falling into the earth today fairly represent the composition of the early planetesimals, then the earth built up of such material must contain, stored within itself, large quantities of gas-producing substances. When the planetesimals struck the earth, the heat of impact must have liberated a small portion of the gases, both from the planetesimals and also from the surface material of the earth. Such gases, liberated by impact, contributed steadily to the earth's atmosphere. As soon as volcanoes began to erupt, more gases were poured into the atmosphere from this additional source.

Beginning of volcanic action.—As the earth grew by gathering in planetesimals, its gravity increased correspondingly, and this force compressed the interior and gave rise to heat. In addition, heat was developed by the decomposition of radioactive substances such as uranium, thorium, radium, etc. Rocks, unlike metals, are poor conductors of heat. The heat, therefore, was conducted outward slowly and the temperature of the interior gradually rose. In time it rose sufficiently to liquefy those parts of the heterogeneous mass which were most easily melted under the conditions of pressure to which they were subject. Small pockets of molten rock developed here and there, while the main mass of the earth remained solid.

The general tendency of liquefied rock materials in the earth is to rise toward the surface. This is partly because ordinary rock expands as it melts, and so becomes lighter than it was in the solid state, and partly because the compressive forces developed within the shrinking earth, aided by the ever acting tidal forces, tend to squeeze the liquid portions outward. The scattered pockets of lava undoubtedly progressed upward with much difficulty. Most of them solidified before reaching the surface. But as they moved upward, they were a means of bringing heat outward; they warmed the rocks in which they came to rest, and so made the way easier for later rising lavas. At the same time it was the more fusible, or soluble, materials which tended to work their way toward the surface, while the less fusible, or less soluble, materials remained behind. In particular, the radioactive substances which generate heat, and hence favor melting, should have progressed toward the surface, in so far as the amount of heat developed from this source and the relative fusibility of this material permitted.

On reaching fractures and other lines of weakness near the surface, which made further movement and escape easy, some of the lavas finally reached the surface, there to burst forth in volcanic eruptions, or to well out quietly as lava flows. The appearance of the first lavas on the surface ushered in the initial volcanic stage.

Beginning of the oceans.—If the earth, when it began to gather in planetesimals, was about one-tenth grown, or in size similar to Mars today, it was not massive enough to hold much water vapor around it. But as it grew, more and more water vapor was collected and, when the temperature of the atmosphere near the earth's surface permitted, some of this vapor condensed as rain. Much of this water later evaporated, and much sank into the ground, but much of it found its way into whatever hollows there were, there to stand in pools.

Even at that time, the earth's surface was not smooth, but consisted of higher and lower lands. Let us see why this was. We have pictured the gradual building up of the earth by the ac-

FIG. 11.—The exterior galaxy known as the Andromeda Nebula—distant abou
1,000,000 light years.

cumulation of planetesimals somewhat as snowbanks accumulate in the polar regions today by successive deposits of snowflakes. Somewhat like the snowflakes, but not too closely like them, the planetesimals did not descend upon the earth equally in all places because much of the planetesimal material was in the form of fine particles which were transported by the winds. We observe that nearly every meteor in the sky today is a short streak of light which comes to an end before reaching the earth. The meteor has been dissipated in the upper atmosphere and reduced to gases and fine dust. Much of this dust remains in the atmosphere for a long time and is carried far by the winds.

The most effective agents which clear dust and smoke particles out of the atmosphere and bring them to earth are rain and snow. Travelers and mountain climbers spending their summer vacations among the high mountains of our northwest, where forest fires are very bad, frequently are obliged to wait for a week or more for views, even of nearby mountains, when the smoke from the fires is particularly thick. After a hard rain the smoke has gone and summits a hundred miles away appear very near through the transparent air.

In general, the larger and heavier planetesimals were but little affected by rainfall and came in more or less uniformly over the surface of the globe. But in addition to these, the fine particles of planetesimal dust floating in the atmosphere, which were an important proportion of the whole infall, were brought to earth in greater quantity upon the areas where rain was frequent than upon the areas where rain was less frequent. The result was to build up the areas of greater rainfall and greater accumulation slightly more than the average, and the areas of less rainfall and less accumulation slightly less than the average. The surface waters came to rest predominantly in the general areas of lesser upbuilding, while the areas of greatest upbuilding for the most part stood above the water. For a time the differences between the large regions of more water which were to become the oceans, and the general regions of more land which were to become the

continents, were not great. But these selective processes went on during all the later stages of the earth's growth, while the earth was growing from a diameter of, say, 6,000 miles to its present diameter of nearly 8,000 miles.

The cumulative effect became important in time, for, once started, the land and water areas, by influencing air circulation and the distribution of rainfall, tended to perpetuate themselves and to increase the differences in rate of upbuilding. Throughout the later growing stages the land areas received more planetesimal matter than the ocean areas and, what was also very important, the lighter material fell in greater proportion on land than in the oceans.

With the division of the earth's surface into some sections predominantly land and other sections mostly covered by water, new selective processes came into operation. The rocks of the land were subject to weathering by atmospheric and other agents, while the rocks covered by water were protected from these processes of decay. On land, the oxygen and carbon dioxide of the atmosphere cause a slow decomposition of the solid rocks which results in breaking them up into the loose fragmental covering which we recognize as soil and subsoil. In this weathering process, rain water plays an important part. The rain sinks into the porous rock covering, percolates through it, and later much of this water reaches the rivers and is carried to the ocean. Suppose that the soils of the earth were simply a mixture of sand and salt; then the water passing through them would dissolve out the salt and leave the sand behind. In time most of the salt would get into the ocean while the sand would remain on land largely free from salt.

The actual conditions in the earth are somewhat similar, but not so simple. Those products of rock decay which most readily dissolve in water are carried to the sea by the waters flowing from the land, while those less easily dissolved by water remain more largely on the land. In the group going to the sea are particularly compounds of sodium, potassium, calcium, magnesium, and some of the iron. In the group remaining on land are particularly silica

(quartz, sand, etc.) and compounds of aluminum, though the separation is by no means perfect.

Although this separation is made because of differences of solubility in water, the process also incidentally separates heavier from lighter material. The compounds of sodium, potassium, calcium, and magnesium which go to the sea are heavier (have higher density) in the aggregate than the silica and the aluminum compounds that remain on the continents. In the course of time, therefore, the materials of the lands become lighter through selective loss of more of the heavier constituents, and the water areas, which receive the constituents of higher density in greater proportion, become heavier. A portion of the dissolved material reaching the sea remains in solution in the ocean water, as we see in the salt, lime, and other substances in sea water today, but the larger part has been thrown down as sediment on the ocean bottom.

This selective process commenced on the earth as soon as there was a division of the earth's surface into certain areas predominantly land and other areas predominantly water-covered. The planetesimals falling on land areas during the building of the outermost 1,000 miles of the earth's mass have been subjected in part to this weathering and lightening process, while the planetesimals falling in the water areas have been protected from weathering and have been mixed with relatively heavier sediments. Becoming deeply buried, portions of these materials have been melted, both beneath the land and beneath the oceanic areas, and igneous rocks of various sorts have resulted.

Thus those portions of the globe which at the outset were slightly elevated as land areas came to be underlain by slightly lighter rocks as the earth grew, and those lower portions in which water collected early became underlain by slightly heavier rocks. In the later stages, when the increased gravity of the nearly grown globe caused compacting in the interior and much readjustment, the heavier oceanic segments naturally sank more than the lighter land segments, thus deepening the ocean basins, while the land

areas stood more prominently above the ocean basins than ever before. In this manner the earth's major relief features, the continents and ocean basins, came to be sharply differentiated, as they have continued to be throughout later geologic history. To-day the continents stand, on the average, three miles above the ocean floors.

The beginning of life.—When the earth reached the stage where water was abundant on its surface and the temperature was favorable, it became suitable for the abode of life. But how did life start on this globe? That is a difficult question which cannot yet be adequately answered. But the geologist can show that the earth in its growing stages offered conditions peculiarly favorable for the origin of living organisms. This is the first step in the solution of the problem and we can go thus far rather easily.

Living tissue is built up chiefly of a few chemical elements which are vital in the processes of life. These are carbon, hydrogen, oxygen, nitrogen, sulphur, and phosphorus. Other elements such as chlorine, calcium, magnesium, sodium, potassium, iron, etc., also play a part, though apparently a subordinate one. Now it is almost startling to note that the meteorites which fall on the earth include several strange minerals and compounds, not found today in the rocks of the earth, which contain precisely the elements essential for life. These peculiar compounds are carbides, phosphides, sulphides, nitrides, and various hydrocarbons. Out in space they are stable and can exist as they are, but in contact with the atmosphere and water of the earth, they are unstable and quickly enter into new combinations. Water coming in contact with the familiar calcium carbide generates the hydrocarbon gas, acetylene. If uranium carbide be substituted for calcium carbide, the result is a gaseous mixture of marsh-gas, hydrogen, and ethylene and, in addition, considerable quantities of both liquid and solid hydrocarbons.

The surface portion of the land during the growing stages of the earth is supposed to have been a loose, incoherent aggregate of fragmental planetesimal matter. It contained an abundance of

these unstable compounds of the critical elements mixed together in close association. Air and water penetrating this porous earth-mantle caused chemical reactions involving carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulphur. These elements entered into new compounds with considerable activity, and in the pores of the soil other activities due to percolation of solutions, capillarity, evaporation, osmosis, and catalytic action undoubtedly cooperated. The ocean, once supposed to be the scene of life's start on this globe, no longer appears to be the most likely place for the beginning of life, for the essential constituents which must be brought together were there diluted and widely diffused and, furthermore, were in a more stable condition. But in the porous soils along the shores and on land, the requisite materials in unstable state were brought into closest interaction, attended by the most favorable conditions for organization into living matter.

The actual beginning of life remains an unsolved problem. The gap between earth materials and living matter has not been bridged. But the study of geology does show that, at a certain stage in the history of our globe, the proper materials for the starting of life were brought together in close association under conditions which then were peculiarly favorable for their interaction and the starting of processes leading to the functions of life.

The more mature stages.—With the development of ocean basins and continents and the establishment of living organisms, the formative stages of our earth approached completion. The planet came to resemble more and more closely the earth of the better known geologic eras and the earth of today. It was still to add several hundred miles to its radius by the infall of planetesimal matter, but the geologic processes which we observe today were in full swing. In the better-known geologic eras the rivers have flowed from the land to the sea and have poured into the sea muds and sands derived from the land. Slowly but ceaselessly material has been removed from the surface of the lands and transferred to the oceans, where it has come to rest as sediment on the ocean bottoms. The continents have been steadily worn

lower and lower by this and other planing processes. If there had been no interruption of these processes, the continents in time would have been cut so low that the ocean waters would have spread completely over them and all plants and animals living on land would have either died or become adapted to life in the sea. There would have been no human race.

But fortunately, before the lands were completely reduced, and land life was engulfed, the continents were uplifted and restored. It is a part of the orderly regulation of the earth's behavior that the very cutting down of the continents leads to their restoration. As the continental segments of the earth become lighter through loss of material, the oceanic segments become heavier by acquisition of sediments. The state of balance between continental segments and oceanic segments becomes disturbed, but the rock substance of the earth has great strength, and unbalancing can continue for a long period of time before the rocks yield. But a rearrangement of the poorly assorted material in the interior of the earth under the force of gravity causes a general shrinkage of the earth, and a yielding of the outer portion of the globe finally takes place.

In shrinking, the different segments do not behave alike. The oceanic segments, as we have seen, are built of slightly denser rock than the continental segments and, in addition, they have been overburdened with sediments brought from the land, while the continental segments, of lighter rocks, have been unburdened by removal of their surface portions. In the general sinking under the force of gravity the heavy oceanic segments sink most, while the light continental segments either sink less, or are squeezed upward relatively by the crowding together of the sinking oceanic segments. The ocean waters withdraw into the deepened ocean basins and the continents are restored to their full areal extent. Thus land life is saved, and the land areas remain a fit abode for the development of plants and animals.

Squeezing the continents affects their borders most. Their margins, in many places, are wrinkled up into mountain chains

TABLE I*

Eras	Periods	Physical Events	Recorded Life	Time: Duration	Time: Since Period Began
	Recent	Erosion dominant on emergent continents.	Man's cultural development.		
	Pleistocene	Widespread glaciation and aridity. (Erosion of the Grand Canyon.)	Development of the species *Homo sapiens.*		1
	Pliocene	Widespread mountain-making, some continuing through Pleistocene.	Probable differentiation of human family from other primates.	6	7
Cenozoic		Himalayas, Alps, Rockies, Andes, made or rejuvenated.			
	Miocene		Culmination of mammals.	12	19
	Oligocene	Marine limited to coasts.	Specialization of mammals for all habitats.	16	35
	Eocene	Erosion of mountains, land-laid deposits at foot of highlands, marine deposits on coasts.	Appearance of modern mammalian orders. Modernized invertebrates.	20	55
Emergence of continents, mountain-making, erosion with much waste collecting in intermontane tracts.					
	Cretaceous, Upper	Marine deposits, beginning of diastrophism which closed Mesozoic.	Specialization and extinction of great reptiles.	40	95
Mesozoic	Cretaceous, Lower	Marine and land-laid deposits.	Angiosperms appear. Largest land animals (dinosaurs).	25	120
	Jurassic	Marine and land-laid deposits.	First birds. Flying reptiles.	35	155
	Triassic	Inland deposits of salt, gypsum, red beds; recording aridity.	Rise of dinosaurs. First mammals.	35	190

Record of the erosion and climatic changes consequent on Permian diastrophism continues through the Triassic. Much sedimentation on the lands.

Paleozoic.............. (Horizontal series in Grand Canyon section)	Permian	Notable emergence of continents, mountain-making, extensive highlands, arid and glacial climates widespread.	Land vertebrates, beginnings of reptilian radiation. Great decrease in marine invertebrates.	25	215
	Pennsylvanian	Freshwater swamp beds interstratified with marine deposits. Beginning of Permian mountain-making.	Climax of amphibians. First reptiles. Primitive insects. Pteridophytes dominant.	35	250
	Mississippian	Marine deposits.	Maximum of fixed echinoderms. First amphibian skeletons.	50	300
	Devonian	Marine deposits, largely.	Abundant fish remains. First record of amphibians (footprint). First woody plants Pteridophytes dominant, primitive seed plants present.	50	350
	Silurian	Marine deposits.	Jawless, limbless vertebrates, probably ancestral to fish.	40	390
	Ordovician	Marine deposits, 60% of North America submerged.	Maximum of extinct arthropod trilobites.	90	480
	Cambrian	Marine deposits.	First known marine faunas, most invertebrate phyla represented. First vertebrates, doubtfully.	70	550

Extensive emergence of continents, mountain-making. (Tilting of tilted series in Grand Canyon section.) Erosion to peneplanation. (*Pu* surface in Grand Canyon section.)

Proterozoic...........	Classification into systems varies with different regions. No correlation by means of fossils possible.	Sedimentary rocks dominant, like later sediments except almost non-fossiliferous. Earliest known glaciation. (Tilted series in Grand Canyon section.)	Fossils very rare and commonly very poor specimens. Primitive invertebrates only.		925
		Long interval when continents were at least as largely emergent as today. Peneplanation. (*Au* surface in Grand Canyon section.) Sediments deposited off the edge of the continents in the ocean basins and now inaccessible.			
Archeozoic............		Much lava and some sediments, since greatly deformed and altered by diastrophism, and greatly altered by enormous granite intrusions Great mountain-making and great vulcanism repeatedly. (*V* in Grand Canyon section.)	Life probably recorded in carbonaceous and calcareous sediments. Algal forms reported. No other fossils known.		1125 1500

* The chart indicates only in a very generalized way the sequence of dominant events in the earth's history. Marine shales and sandstones necessarily record contemporaneous erosion and, therefore, require lands during even the greatest submergences. Most of the great emergences are known to be bridged over in limited areas by sediments. Lack of specific statements as to vulcanism and diastrophism do not indicate their non-occurrence everywhere during or between periods of sedimentation on the continents. The evolution of life is very inadequately indicated. Time estimates, after Barrell, are based on radioactive decomposition of uranium.

The rocks in these wrinkled portions near the coasts, when strained too much, break and large masses slide over one another along fault planes, producing earthquakes. Recurring earthquakes are but minor incidents in the growth of a mountain range. In these same regions, where the surface rocks are moved and fractured, molten rock from below most readily finds its way to the surface, producing volcanoes and lava flows. Thus, through the slow operation of closely related processes, are fashioned the grander features of the earth's surface. The continents, plateaus, mountain ranges, volcanoes, with incidental earthquakes and destructive eruptions, are all the outcome of an orderly operation of earth-forces. After their elevation, the higher scenic portions of the lands are vigorously attacked by another group of equally orderly processes which slowly wear them down and, if allowed to continue indefinitely without interruption, would completely obliterate them. But here the beautifully regulated system of balance comes into play. The very wearing down of the lands leads to their restoration. They are given another long period of life and, millions of years later, when that period of life has run its course, the lands are started afresh on a new cycle. Cycle follows cycle. During these ages upon ages, of continents high and continents low, the great drama of life goes onward through its acts and scenes. As we know that there have been many acts and scenes in the past, so we may believe confidently that there will be many acts and scenes in a long future to come, and that the human race will have almost unlimited opportunity to develop along its chosen lines. The story of our earth, started on its long career in this chapter, will be unfolded further in the next chapter.

SELECTED REFERENCES

1. T. C. Chamberlin, *The Origin of the Earth* (University of Chicago Press, 1916).

2. F. R. Moulton, *Introduction to Astronomy*, rev. ed. (The Macmillan Company, 1925), chap. xii, pp. 407–61.

3. T. C. Chamberlin and R. D. Salisbury, *Geology*, II (Henry Holt and Company, 1905), pp. 1–119.

CHAPTER III

GEOLOGICAL PROCESSES AND THE EARTH'S HISTORY[1]

J HARLEN BRETZ

GRADATION

Our earth is a body distinct from other parts of the universe, a ball, or spheroid, swinging ceaselessly on through space from a beginning unknown to an end unknown. It is changing constantly in position; rotating before the blaze of the sun like a giant roast on a spit, and receiving radiant energy in total amount almost incomprehensible.

This great rotating earth-ball is composed chiefly of solid matter (the lithosphere), but it possesses an outer portion, a mere film, of gaseous matter (the atmosphere) and another still thinner and discontinuous film of liquid matter (the oceans or hydrosphere). Though relatively insignificant in mass, the atmosphere and hydrosphere are of the greatest importance in the production of changes on the exterior of the earth. These changes result from circulations in the liquid and gaseous films.

These circulations of water and air are caused by the unequal distribution of the solar energy on the surface of the earth. The unequal distribution, in turn, is the consequence of several factors: rotation of the earth, varying angles of incidence of the solar rays, varying distribution of land and water, etc. These factors might be traced back still farther. Varying angles of incidence, for example, depend on the curved surface of the earth (the sun's rays are sensibly parallel, so far as the earth is concerned) and on the existence and essential constancy of tilt of the earth's axis from perpendicularity to the plane of its orbit. Though we shall

[1] Part of this chapter has been modified from an article by the author in the *Scientific Monthly* for March, 1924.

pursue this analysis no farther here, there are causes for these causes and causes for their causes, *ad infinitum*.

The various circulations of air and water drag bottom to a large extent. The underlying lithosphere suffers from this friction and pieces of the solid material are moved from place to place. Since gravity has its grip on things, such shiftings of solid fragments are prevailingly from higher places to lower. This causes degradation, or wearing down, on the higher places, and aggradation, or building up, on the lower places. The process in its entirety is called gradation. Its tendency is to level the surface of the lithosphere.

Specific air and water circulations are termed agents, and receive specific names. Air in motion is wind. Water which falls as rain and flows down the land slopes is concentrated into streams. Water which falls as snow and accumulates in such thicknesses as to be compacted into ice may move slowly down the land slopes as glaciers. Water in the oceans and lakes has its surface thrown into waves by the friction of the wind. These waves, encountering land, are also agents of gradation. The rain water which enters the soil and the rock and moves slowly through it, largely to emerge in lower places as springs and seepages, is the agent ground water.

Weathering.—In most regions the surface of the lithosphere is composed of an incoherent material which is easily excavated, easily plowed, and easily eroded by running water. Streams are muddy in proportion as they carry this loose material. But if excavations go deeply enough into the unconsolidated soil and subsoil, consolidated rock, or bedrock, is encountered. Where slopes are steep enough, the bedrock may have no cover of loose material. Why is there a cover or mantle anywhere?

The answer need not be sought in a book. Any observant person may see that rock is not "living" or "eternal." Fragments are split off from cliffs by the freezing of water in cracks and pores, by the growth of plant roots which have penetrated cracks, by the stresses caused by unequal heating and cooling from day to night, and by the sheer pull of gravity. These destructive changes exist

on gentler slopes as well, but gravity is less effective in removing the débris. The slopes become covered with a mantle resulting from the destruction of once firm rock.

The physical changes, just outlined, are supplemented by chemical changes. Oxygen, water, and carbon dioxide from the atmosphere enter into combination with the constituent minerals of the rocks, reorganizing them to make oxides, hydrated compounds, and carbonates. Almost all such changes reduce the coherency of rock and it gradually crumbles. The sum total of all methods, physical, chemical, and biological, which destroy indurated rock, is weathering. The weathered débris still is rock, for rock is the material of the lithosphere. It still is solid (not liquid, not gaseous), but it is not consolidated. It is mantle rock. If it remained in the place where it was formed, it eventually would be thick enough to protect the deeper-lying portion of the bedrock from further attack, and weathering would cease. But here the transporting agents appear and play their part in gradation.

Wind.—Of the different agents of transportation, the wind is universally active. Its characteristic effects, however, are rather limited in distribution. The density of the air is only 1/800 that of water and its buoying and frictional effects are proportionately less. Only the finer particles of mantle rock can be moved, and even these if damp or covered with vegetation will not be transported. Arid regions offer the most favorable conditions for wind work. Sandy shores whose fair-weather winds are off the water may exhibit the work of the wind, as also may sandy bottom land along rivers.

Wind-blown sand commonly travels close to the ground. The journey of any one particle is a series of leaps as the gusts come and go. Consequently any obstacle to the wind is likely to cause deposition of sand to the lee. The sand mound soon is an obstacle in itself and the deposit may grow until a hill a hundred feet or more in height is built entirely of the wind-transported sand. These dunes, however, are not necessarily fixed objects. Sand is swept up the windward slope, over the summit and into the quiet

lee, where it comes to rest. Thus the windward slope is eroded, the lee slope aggraded, and the dune advances in the direction of the stronger fair-weather winds. Dunes along shores and in river valleys commonly do not get far from their limited source of supply before vegetation succeeds in holding them down.

Sand grains are about the largest particles transported by the wind. Dust is much more easily picked up and travels much farther and in greater quantity. Most dust is contributed by the mantle rock of dry regions. But, unlike dune sand, which fails to escape from localities favoring its collection, dust is transported so easily and deposited so widely that every land region may have dust particles from every other land. Dust deposits may form mantles of the very fine-textured material a hundred feet or more in thickness over considerable areas. The loess of the upper Mississippi valley, of the Columbia Plateau, of Mongolia and northern China, and of the Danube and Rhine valleys is probably dust that has settled from the air. The significant thing about the transportation of dust, however, is that while one-fourth of the surface of the earth may yield it, receive it back, and yield it again in great cycles of change, all dust which settles on the other three-fourths of the earth's surface (the oceans) is a definite loss of land materials.

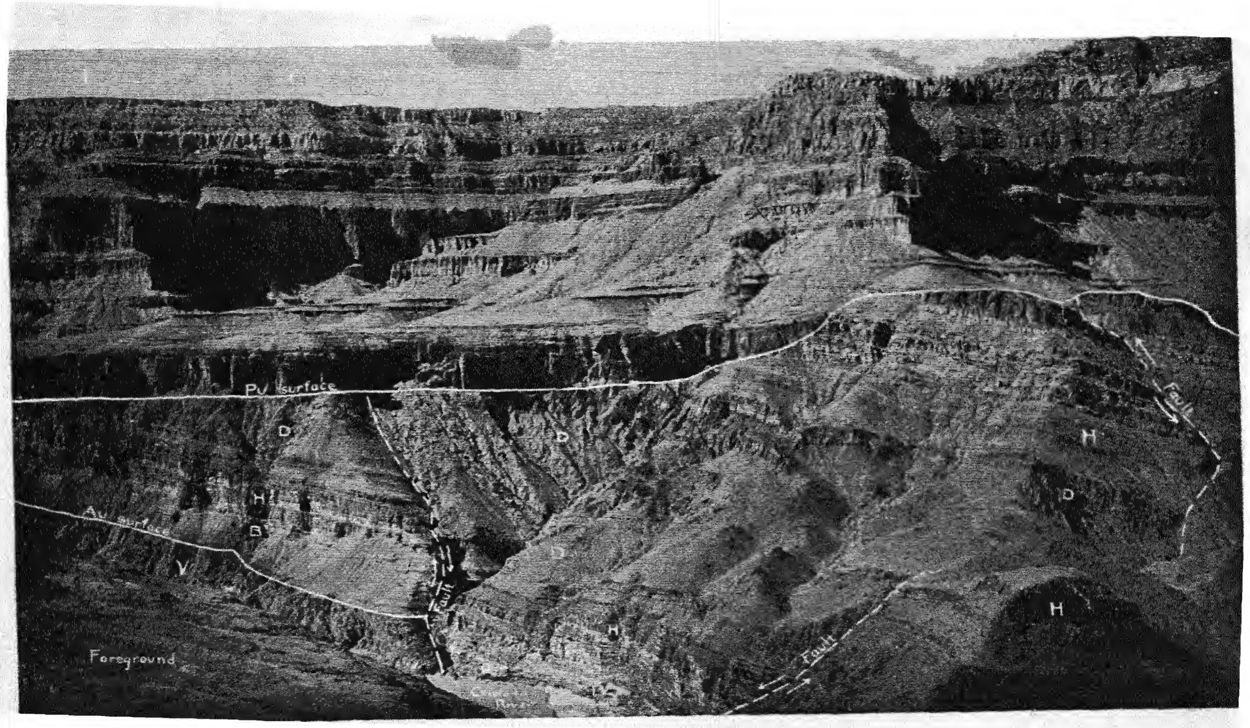
Running water.—If all the rain which fell on an average land area remained on the surface, it would stand approximately 3 feet deep in a year's time. But in most places it flows off the slopes and eventually to the oceans. Convergence of slopes means convergence of the run-off and the formation of rivulets. These, by further convergence, form streams. This running water is the most effective agent of erosion and transportation of rock débris on the earth. The Mississippi River carries 1,000,000 tons of mud and silt to the Gulf of Mexico every 24 hours. If carried by railroad, it would require more than twice the number of freight trains which enter Chicago, the world's greatest railroad center, in the same length of time. And though the Mississippi is a great river, it contains only a small fraction of the river water flowing from all the

lands. The degradation of North America by streams is estimated to be proceeding at the rate of 1 foot in 9,000 years.

Obviously the rate is more rapid near large streams, for they are concentrations of the run-off. And the more a valley is deepened and widened and lengthened by the erosion of its stream, the more water flows into it and does this work of erosion. There must be a limit somewhere. No stream can erode below sea-level, nor to sea-level except at its mouth. As streams deepen their valleys, they reduce their gradients, hence flow more slowly and erode less and carry less mud and silt.

When the work of erosion starts, the region in terms of erosion is young. It has but few streams and these have but few tributaries. Gradients are high and valley-deepening is rapid. Tributaries develop and more valleys are etched out until at maturity every part of the region is well drained. The main streams first reach their depth limits, later the tributaries, and finally the wet-weather rills on the hill slopes. If given time enough, streams bring their drainage areas down to slopes so gentle that erosion virtually ceases. The region, perhaps once high and rugged, becomes a low rolling plain, an old land. The peneplain now produced is the inevitable product of uninterrupted stream erosion, and the ocean basin is the recipient of the débris. Most of this stream work is rendered possible by the concomitant weathering of the bedrock to incoherent mantle rock. We shall return later to a consideration of the wastes deposited in the oceans.

Ground water.—Not all rain water flows from the slopes on which it falls, for mantle rock and bedrock contain pores and crevices into which rain water may penetrate. If we have no satisfactory supply of water at the surface, we generally secure it from the ground by digging or drilling a well. Below a certain depth, which varies with localities, the hole will fill with water which seeps in from the rock penetrated. Ground water circulates slowly under the pull of gravity and most of it escapes eventually to the surface at some place lower than where it entered. During its subterranean journey the water, aided by atmospheric gases and



U. S. Geological Survey

FIG. 15.—A typical cross-section of the Grand Canyon

organic substances in solution, and perhaps by higher temperature, dissolves and removes various minerals from the rocks. Complete removal in quantity may leave large caverns, such as Mammoth Cave in Kentucky. Selective removal may simply make the rock porous. Reprecipitation of minerals may occur, and give rise to veins of ore, stalactites in caves, etc. When the ground water escapes it joins the streams, and the mineral matter remaining in solution is taken to the ocean. Streams carry about one-third as much material in solution as in suspension. Like the wind-transported dust and the river-borne mud, sand, and gravel, this dissolved material is a definite loss to the lands. The work of ground water is another part of the general attack which wastes away the land masses of the earth.

Glaciers.—Any region whose temperature and precipitation are so related that more snow falls in winter than melts in summer will have glaciers, for glaciers are simply the accumulations of the residual snow of many years, compacted into ice and moving down slopes under the urge of gravity. In mountainous regions the snow accumulates in the high valleys where it changes into ice. Thus the common alpine, or valley, glacier is formed. It is, in appearance, a great river of ice which moves with extreme slowness, averaging a few feet a day. In other places the ice may grow to such thicknesses that the entire region becomes buried and the ice-sheet type of glacier results. This is more likely to occur in plains and plateaus than in mountains. Since there is no concentration in valleys, the ice-sheet may move but a few feet a year.

Despite its sluggishness, glacial ice erodes profoundly. A rock fragment, frozen in the bottom of the ice, is held against the bedrock below by both its own weight and the weight of all the ice above it. This is in notable contrast with stream erosion where the fragment does not transmit the weight of the water above it and is itself buoyed up by the water. The moving ice is a gigantic rasp and the débris it produces is only physically fragmented. Thus there is no weathering beneath a glacier. In composition, the

glacial débris is identical with the uneroded bedrock from which it is derived.

Valley glaciers bite deeply into the rugged, mountainous country in which they are formed. They fill their valleys from side to side and by downcutting, and to some extent by undercutting, they maintain very steep valley slopes, almost walls. The cross-section of a glaciated valley is much like the letter U. In contrast with this, stream valleys commonly have flaring valley slopes, more V-shaped in cross-section. Sapping or plucking at the upper end of a valley glacier also undercuts and produces the great amphitheaters in which the alpine type of glacier heads. Divides between adjacent valley glaciers are likely to be almost knifelike in their steepness and narrowness. Continued erosion commonly diversifies such divides with sharp peaks of the Matterhorn type. Mountains sculptured by valley glaciers, whether of the present or the recent past, thus have a topographic expression quite unlike that produced by stream erosion in similar situations. An excellent example of strongly glaciated mountains is found in the Rocky Mountains of Glacier National Park.

Glaciers, unlike rivers, seldom reach the sea. They are more commonly melted as they descend into lower altitudes. Their débris, therefore, is deposited largely on the land, and constitutes a type of mantle rock notably unlike that produced by weathering. Some of the glacial load is carried off by the water from the melting ice, some may be left for thousands of years after the ice has disappeared, to be removed more leisurely by rivulets and streams which make their appearance as the climate becomes warmer. The streams of the northern United States and southern Canada are working today largely on the mantle rock (glacial drift) left tens of thousands of years ago by the great North American ice sheet.

Glaciers, therefore, are active agents of destruction of the bedrock. They degrade the highlands vigorously by deepening valleys and steepening and narrowing divides; as ice sheets they may override all the hills as well. The wastage they produce is likely

to be carried to the sea sooner or later, and is then a definite loss to the lands.

Waves and shore currents.—The shoreline is the scene of another successful attack by gradational agents; in this case, the waves and the alongshore currents produced by them. Waves are caused by the frictional drag of the wind over the surface of the water. In open water the form of the wave travels with the wind, though much less rapidly, but the water particles themselves move only in oscillatory fashion, without advancing with the wave form. The energy of the wave motion produces no gradational results except where a shore is encountered. Here erosion at the water level occurs. This undercutting, like that performed by glaciers and streams in some situations, removes the buttressing lower part of whatever land slopes may have been there originally, and gravity then pulls down the upper part to a slope determined by the coherence of the rock. The new slope is steeper than the old; it may be vertical or even overhang. In any case it is a wave-cut cliff, or sea cliff. The débris contributed to the waves comes from the whole face of the cliff; it straightway becomes tools with which the waves may greatly increase their erosive work. The tools themselves wear out, though constantly replaced, and the grist of the wave-mill is easily carried off into deeper water where it settles as mud and sand.

We may speak of a cliffed shore as retreating before the wave attack. Such retreat surrenders territory to the enemy, decreasing the area of the land. Development of a conspicuous cliff necessarily requires the development of a nearly horizontal terrace beneath the waves where the vanished land once stood. As retreat continues, the area of this submerged terrace increases and, from a mere wave-cut bench, it becomes a considerable submarine plain of erosion.

It is true that some shores are being advanced, or built out, into the water. Accumulations of beach sand and gravel may be made by the shore currents that are produced where prevailing winds (and their waves) strike diagonally on the land. But the

finer materials that are carried off into deeper water are a definite loss, never by the work of shore agencies to become land again, and, all told, the retreat of shorelines exceeds the building out of coasts. With adequate time and no interruptions, the lands of the earth would inevitably be destroyed by the waves, only a submerged plain of erosion remaining.

Summary of erosion.—We have now very briefly reviewed the chief agents of degradation though many of the interesting and intricate details of their methods have been omitted. Nor have we more than hinted at the study of Nature's scenery as a record of past events. We appreciate, however, that

> The hills are shadows, and they flow
> From form to form, and nothing stands;
> They melt like mists, the solid lands;
> Like clouds they shape themselves and go.

Everywhere is change, orderly change. It is exceedingly slow as human lives are reckoned, slow even as the lives of nations are measured. But we cannot accept the notion that the earth's surface is a finished product, as though turned out of a factory a few thousand years ago. We must make new interpretations and for them we must rely wholly on our observations and our reason.

One conclusion which we are forced to accept is that *terra firma* must decrease as surely as degradational agents work—"as surely as the sun shines"—for it is the sun's radiant energy which changes the ocean's surface film into gas, which stirs the atmosphere into winds, and which is responsible, therefore, for wind work, for waves and shore currents, and for rains, rivers, ground water, and glaciers. The ultimate consequence of this activity is the destruction of the land. The débris which reaches the ocean in various ways displaces an equal volume of water; in other words, it raises the ocean level. If our present continents were worn down to sea-level and the débris were dumped into the margining oceans, the ocean surface would be raised 650 feet. A universal spread of the hydrosphere thus is inevitable if the

degradational attack continues long enough and no other factors enter into the problem.

Yet there is land today, perhaps as much land as the earth has ever had. And much of this land is lofty and rugged and youthful. Is not the earth old enough, then, for the erosional agents to have yet done their work? Or are there other factors which offset the work of erosion?

The answer to the first question is found in the existence of large land areas of low relief, essentially planes, beneath which are rocks of very different degrees of resistance to erosion. In only one way could they have been formed. They have been scrubbed down by erosion and are now in that penultimate stage of erosion termed the peneplain. Their streams are at base level. They have almost ceased to erode. Yes, the earth is old enough. We shall shortly review evidence which shows that peneplanation has occurred repeatedly in the past, that the time necessary is but a small fraction of the total recorded geological history, that land areas at times have been reduced to one-half or one-third of their present extent. Since the earth has youthful mountains and plateaus today, the suggestion in the second question is confirmed—there must be other factors which offset the work of erosion, which elevate existing low lands and which even restore submerged areas to the condition of land. Also, since peneplanation has been repeatedly accomplished, these antagonistic factors must be quiescent for intervals long enough for the cycle of erosion to be run, must be rhythmic in their occurrence. We are now ready to consider another great geological process, the antithesis of gradation.

DIASTROPHISM

Now and then the elaborate structures which men build to live in and work in suddenly come tumbling down upon them. Perhaps an entire city is wrecked in a few minutes. Formerly an angry deity was blamed; now we say an earthquake is responsible. But what causes an earthquake? Most quakes are the result of a fracturing and slipping in the subjacent bedrock, that is, faulting.

The stressed condition which caused the fracture and displacement is then relieved, at least for a few years or decades. But it may redevelop and another quake occur in the same region. It is clear that adjustments of some sort are occurring in the lithosphere, and that the forces involved are adequate to break the strongest rock and to move enormous masses of it.

Less spectacular than earthquakes but just as convincing are changes in level along ocean coasts since human history began. There are stone quays and other landing places, built centuries ago, which are now high above and well back from the shoreline. Other stone structures, built on the land, are submerged. And prehistorical evidences of uplift or subsidence are plentiful. Long estuaries like Chesapeake Bay record a sinking of the land and a flooding of an earlier river valley. Limestone crowded with fossils of marine animals but now lying far inland and perhaps high in the mountains tells of an uplift of the land, or a lowering of the sea-level, or both, totaling hundreds or even thousands of feet. Such movements in the lithosphere, whether slow or rapid, are termed diastrophism.

The really surprising feature of the diastrophic record in the rocks, however, is that the largest displacements seem to have been horizontal rather than vertical. Many of our mountain ranges are structurally enormous wrinkles of rock, rock which undoubtedly once was flat-lying sand or mud in some shallow sea. Such great folds are very probably the result of great compression tangential to the earth's surface. The associated compressive faulting along nearly horizontal planes, amounting to miles in some places, seems clearly to show that in the making of a mountain range, the region has been shortened at right angles to the line of the range.

If the folded mountain structures do record such shortening, the simple mechanics of a shrinking earth seems best adapted to explain it. Originally it was conceived that cooling of a molten earth caused the shrinkage. But the rate at which heat is lost from the interior of the earth is much too slow to produce the

amount of wrinkling that has occurred during geological history. And it is altogether likely that the earth, although radiating heat into space, may be generating quite as much as it is losing. Furthermore, the amount of radial shortening has been very different in different places, as it should not be by this hypothesis. We must look farther for causes of the shrinkage.

Radial shortening—have we direct evidence of this? Or is the conception only an inference drawn from the folded tracts? The direct evidence, we believe, lies in the existence of those grandest relief features of the lithosphere, the continental platforms and the ocean basins. Two-thirds of the surface of the lithosphere is ocean basin; one-third is continental platform (land and the shallow margining seas). The oceans average two miles and a half in depth, the lands a half-mile in height. There must be some cause for these great elevated and depressed tracts, separated by a vertical interval of three miles.

When we investigate this matter we find a very strange thing: the lithosphere beneath the ocean basins is composed of heavier material than that under the continental platforms. This has been shown by swinging a pendulum of proper construction under controlled conditions. A given pendulum has a slightly shorter period of oscillation over the ocean basins than over the continental platforms. Furthermore, the lavas of oceanic volcanoes have a greater density than those of the continental platforms. The difference in specific gravity between these contrasted regions of the lithosphere is about 3 per cent. Why this is so, we do not yet definitely know. It is only one of many, many things about our earth that we do not understand, perhaps never shall fully understand. But the bearing of the fact on our present problem is not lost on us. The heavier portions of the outer lithosphere are the lower portions. They are lower because they are heavier! If we conceive of the earth as made up of great wedges whose apices are within the spheroid and whose bases constitute the continental platforms and the ocean basins, and of the earth's interior as decreasing in volume, then the heavier wedges or segments should settle

more than the lighter, and the hydrosphere should collect over them.

This settling together of the great segments, as the interior shrinks, is held to be the fundamental cause of diastrophism. The horizontal thrustings recorded in rocks of the land are consequent on this wedging together. The great earthquake regions and the great folded mountains are in general adjacent to, and parallel with, the continental margins where lateral crowding should be at its maximum. Minor faulting and warping in diverse directions is to be expected, for a continental platform is far from being unyielding. Not all horizontal movements should necessarily be compressive, not all vertical movements should parallel the coasts. One coast line may be slowly rising while another is sinking and a third is stationary. It is the large view which we seek; we must not lose sight of the forest because of the trees.

Two antagonistic, antithetic processes are occurring before our eyes; gradation, which destroys the lands; diastrophism, which renews them. Though diastrophism has the upper hand today, there appear to have been times in the past when gradation proceeded far along in its task before it was interrupted. Times of diastrophic unrest appear to have been separated by long intervals of diastrophic quiescence. This is another subject to which we shall return.

VULCANISM

Not long ago men believed that they dwelt, a bit precariously, on the congealed crust of an earth of molten rock. Terrible evidences of the subterranean heat were at hand. Did not Vesuvius wipe out two proud Roman cities in A.D. 79? Were not volcanoes the safety valves for this interior of incandescent liquid? Doubts, however, began to arise as closer study of the earth was made. The famous earth-tide experiments of Michelson, Chamberlin, and Moulton, in 1913, demonstrated that the deformation of the earth (not the oceans) by the pull of the moon is that of an elastic rigid body, not a liquid body with a shell or crust. The seismo-

graph, which records and measures earthquake shocks shows that the earth transmits vibrations as no liquid could do, and that it has the elastic rigidity of tool steel. The phenomena of vulcanism, so simply explained before, immediately became a very difficult problem. Though our knowledge of vulcanism increases yearly, the problem of its cause is far from solved. Indeed, science never solves problems; for the more we learn, the more contact we make with new, unknown territory. Our problems are simply advanced toward a solution.

What we now know of vulcanism leads us to believe that most volcanic vents are supplied from separate sources, that the molten rock is produced from previously solid material, that it is not truly molten, but is a mutual solution of minerals and gases at high temperatures (magma), that the depth of generation of magma is probably a few tens of miles, and that the gases are in part new contributions to the atmosphere, not simply a return of materials formerly on the surface.

The rise of magma is very slow and probably much like that of a liquid, and the violent eruptions are due to the more rapid rise of gases which charge the upper part of the magma until it becomes highly explosive. Not all magma becomes lava, i.e., reaches the surface. Much of it chills beneath a cover of rock and there becomes welded into the lithosphere, an intrusive mass of granite or other coarse-grained igneous rock. Erosion may later expose it and the insatiable curiosity of science may then decipher the record.

The origin of magma and the location of volcanic fields seem traceable to the same mechanism which we hold responsible for diastrophism. The earth body, growing by infall of heterogeneous planetesimal matter, had great possibilities of condensation and compression. Physical and chemical changes toward greater density released energy in the form of heat. Thus was produced the earth's internal temperature which, for aught we know, may still be increasing. Eventually, in favored places, mutual dissolving of solid material occurred to make the silicate solutions we call

magma. Migration of such liquid rock toward the surface may largely be determined in place and in time by the weaknesses produced by diastrophic adjustment. Many volcanic vents are clearly located on such structures. The Pacific is often described as surrounded by a "ring of fire," as it is also by young mountain ranges and tracts frequently shaken by earthquakes.

GEOLOGICAL HISTORY

Let us suppose that one wishes to know what the earth's history has been and how long it has run. What does he do? He goes to a library for a book or he attends a series of lectures on the subject. But the writer or lecturer may both present information which they learned from other writers or speakers, and they in turn from others. Is this chain traceable back to a first authoritative book or lecture? Where did the information come from before it was embodied in print?

Geology does have a first authoritative book of facts—but it is not in any library! It is in the rocks of the lithosphere. No author's personal equation need be allowed for when you read it; no emotional reactions warped the original historian's selection of facts. Yet this unbiased book is exceedingly difficult to read, for it is written in hieroglyphs and it is very fragmentary. Its deciphering is far from complete, and many fragments previously unknown are constantly being collected and pieced together.

We see each of the three great geologic processes recording its manifold phases in the rocks. Degradation sculptures the lands and its shop waste goes into the making of many kinds of stratified sediments. Vulcanism produces a great variety of igneous products, quite unlike the sedimentary rocks. Diastrophism deforms both igneous and sedimentary rocks in unmistakable fashion. We witness many of these changes; no one can gainsay our observations. If we find closely similar land forms, rocks and rock structures, of whose origin there were no witnesses, surely we are justified in reading from them a record of events similar to those now occurring.

The record of one section.—Let us examine briefly a typical section in the outer lithosphere to see how this works out in a concrete case. The section (Fig. 15) is a portion of the north wall of the Grand Canyon in Arizona. The Colorado River has trenched a mile deep here. For nearly half a mile it has cut down through horizontal stratified sedimentary rocks: limestone, sandstone, and shale. The limestones contain fossil corals and other marine organisms. Below these level strata, the river has eroded another half-mile or so through tilted sedimentary rocks: quartzite, limestone, and shale. Below these it has entered a crystalline rock without stratification.[1] There is an irregular contact between the upper level strata and the lower tilted strata, and another between the tilted strata and the crystalline rock *V* at the bottom of the great gorge. There are two faults in the tilted beds, for whose apparently irregular courses the perspective is in part to blame. The river at the bottom is a swift stream with about 2,000 feet yet to fall before it reaches the sea.

What do we read from this section?

1. The valley is narrow at the bottom and very steep-sided. This fact and the swift current spell youth. The sky-line is level; few tributaries have cut into it, another evidence of youth.

2. The upper horizontal strata were once below sea-level, for they contain marine fossils. They have been elevated without deformation to their present altitude of about 8,000 feet. Either that or the sea-level has been lowered the same amount. Let us call it elevation.

3. The time for the accumulation of this half-mile, approximately, of horizontal sediments must have been enormous. We say without hesitation "millions of years" and we have good evidence for the conclusion.

4. The level series was deposited on an irregular surface of the tilted series. Such a relationship is styled an unconformity. Be-

[1] This is *V* in the illustration. The area in the lower left is a part of the foreground on the near side of the river and well above river level. The river flows between it and *V*.

fore that deposition began, there was clearly a hill in the right-hand part of the view and a lower plain to the left. This buried topography was produced by erosion of the older tilted strata (as shown by their beveled, or truncated, edges) before the level series above was deposited.

5. The deposition of the lower series, which is thicker than the upper, probably required more time.

6. This deposition no more built the lower series in their present inclined position than it produced the truncated edges. Therefore, the tilted series, originally horizontal like the overlying beds, was deformed by diastrophic movement after its deposition, but before its erosion. The faulting apparently occurred at the same time. It certainly did not occur after the deposition of the upper series, or the offset would show in them and in the contact *Pu*.

7. There was an episode not easily deciphered from the photograph. *D* is a stratiform mass of crystalline igneous rock a thousand feet thick that was forced laterally between the strata of *H*, splitting the formation *H* into two parts. The heat of the intrusion baked the sedimentary *H* for a hundred feet or more both above and below the contacts. This vulcanism occurred after the deposition of the lower series but before the faulting; probably, therefore, it antedates the tilting.

8. The contact *Au* of the lowest sedimentary formation *B* on the crystalline rock *V* is another plain of erosion, like *Pu*.

9. The structures of *V*, not shown in the photograph, indicate that it was once buried very much farther below the surface than it now lies, and there under great pressures and high temperatures it was so greatly altered and recrystallized that we cannot determine now whether it was originally sedimentary or igneous rock.

Let us now note the larger significant features of this history. We have not yet read the whole story and incidentally we have read it thus far in reverse order. It was diastrophism, operating at great depth, which crushed and mashed and recrystallized the basement rock *V* and left it where degradational agents could

attack it. The ancient highlands, which were the original cover of *V*, were removed by a vastly greater amount of erosion than the Colorado has performed in cutting the canyon, a much greater amount than that which made the *Pu* land surface. This original cover was carried away by the ordinary slow action of weathering, running water, wind, etc. The time required is almost inconceivable in the units with which human history is measured. When we discover that everywhere in the canyon the *Au* surface is a plane, we realize that we have discovered a buried peneplain of such hoary antiquity that the expression fails utterly to convey our meaning. Evidence to be noted later indicates that this peneplanation was completed probably more than 700,000,000 years ago.

Succeeding the great period of erosion was another period of similar magnitude during which the lower sedimentary series was deposited. That the sea was here we suspect but cannot prove, for there are no marine fossils known in this half-mile of sediment. The time was so far back in the earth's history that apparently plants and animals had not yet developed dense, hard, fossilizable parts.

Then diastrophism again awakened and the lower series of sediments was faulted and tilted, the *Au* peneplain with it, of course. When more of the canyon is examined and the eroded portions of the tilted rocks reconstructed, we are perhaps a bit surprised to find that this second recorded diastrophism erected mountains here thousands of feet in altitude.

Again a long period of quiet ensued and this second great highland tract was humbled into dust. Another peneplain was eroded, on which stood a few surviving low hills, the stumps of the former mountains. Farther along the canyon and not shown in the picture this second erosion cycle witnessed the removal of all of the lower sedimentary series so that the *Pu* peneplain there is cut into the basement rock and the whole record of one grand pulsation of earth history is missing. If the ancient mountains had been elevated a few thousand feet more, so that the base level of the *Pu*

peneplain had been in the crystalline rocks throughout, we should have no record of the *Au* peneplanation, or of the deposition of the lower sedimentary series, or of the making of those former mountains. This is what we mean, in part, when we say that earth history is fragmentary.

The mountainous land produced by this second diastrophism was worn down so low after long ages that displacement of the sea water by deposition, or a subsidence of the lowland, or both, allowed a shallow ocean to roll in over the *Pu* peneplain, and the deposition of the upper series was started, the débris coming from the erosion of other land areas. In these seas lived shellfish and corals, whose fossil remains are of vast importance to the geologist.

Today, the rocks of this region are lifted higher above sea-level than ever before. The streams of the *Au* cycle, and the *Pu* cycle never cut as deep as the present great gash, itself with hundreds of feet yet to go. Should a stillstand of the region persist until the present cycle were run through to the peneplanation of old age, the whole record that we have read would be erased and the new peneplain would be in the crystalline basement rock.

The Grand Canyon section is but an example, and a very simple one at that. In the preceding paragraphs we have hardly begun its deciphering. And when fully deciphered, it will be only a partial record of the events of this particular region. We do not have many sections as clean-cut as the Colorado Canyon. But we do not need them. We may read from the innumerable smaller valleys of our mountain ranges, or we may piece together the outcrops on the plains, to which we add data from mines and deep wells. Indeed, the earth's story as we now have it is a laborious piecing together of the fragmentary histories of various sections.

Correlation of sections.—This piecing together—how can it be done? Can we say that a red sandstone in this region is a part of the same deposit as a red sandstone in another? Can we safely assume that limestone was being deposited in both regions at the same time? Dare we assert that a particular unconformity records

the same period of land conditions as another unconformity in another region? No; this would lead nowhere. We must have something which is common to all strata, something which has not varied greatly at any one time but which has changed gradually and progressively during the march of events, something by which we may correlate our piecemeal record. Here fossils are invaluable. Without them, a history of the earth could not be deciphered.

A fossil is any trace or remains in the rocks of organisms of the past. Fossils commonly consist of the hard parts of organisms, for these decay slowly and are more likely to become buried before destruction. But the imprint of a plant leaf, the footprint of an animal, the boring of a worm in the beach sand, if preserved in the sedimentary rocks, is a fossil. Burial is a prerequisite for preservation. This usually is accomplished in the ordinary procedures of sedimentation. Petrification, or the replacement of organic substances by minerals in ground-water solutions, is very common though not essential.

Fossils were variously and engagingly interpreted in earlier days. They were ascribed to fermentation or exhalations of the earth, and to the influence of the stars; they were considered as imperfect products of the haste of a six-day creation, and as relics of Noachian organisms that died in the great inundation. It has even been argued that the fossils, which seem so clearly to record an immensely long evolution of life on the earth, were designed and distributed in this fashion, telling a story at variance with a literal Genesis, to test our faith in Holy Writ. Ancient notions still persist in our thinking because men seek defense of favored ideas and shut their eyes to the truth. Leonardo da Vinci, who was a contemporary of Columbus, first clearly stated that marine waters had been, and marine forms had lived, where fossils now are found. But not until a century and a quarter ago was our knowledge of fossils more advanced than this simple conception. Then a land surveyor and civil engineer, named William Smith, discovered that by means of fossils he could correlate the strata

on the south coast of England with those on the east coast, though direct tracing across was impossible. He found that each formation could be recognized by its particular group of fossils and that most of the fossil species were limited to definite horizons or formations. Here was the first real step toward reading a chronology of the earth; here were date markers!

The rhythm in the record.—Smith did not realize the biological significance of his discovery. No one then did, for too little was yet known. But as the paleontologist worked out the fossil faunas, the stratigrapher used the data to identify formations in widely separated localities as of this age or that, the structural geologist to date the diastrophisms of the past, and the biologist to support that fundamental conception of long-continued gradual organic change—the theory of evolution. Geological systems of strata were established, whose faunas were still more strikingly distinct from one another than were those of adjacent formations in a system. Each system recorded a period. And the different systems were found generally to be separated from one another by unconformities. Unconformity is a record of erosion, of land conditions. Hence the large generalization that the continents, where we read the record, have repeatedly stood well above the ocean level and have repeatedly been partially submerged beneath shallow seas. And that for all continents these alternations apparently have occurred at approximately the same times. And that times of marine withdrawal have been times of mountain-building in some place or other. Diastrophism, responsible for this shifting of land and water areas, has been rhythmic and world-wide. Diastrophism, therefore, has been a consequence of internal changes, occurring at intervals, which have systematically affected the entire surface by pulling down the ocean basins more than the continental platforms.

Biologic response to the rhythm.—The changes in faunas across the time gaps of the greater unconformities are so great that in some cases the doctrine was once entertained that there was complete annihilation of living forms at the time of the break

and a new creation after the break. Though we now know that some invertebrate forms have lived through several geological periods, in general there are striking faunal changes from period to period.

Consider the situation of the widespread shallow-water marine faunas at the time diastrophism awakens. These shallow seas are drained, and the forms migrate or perish. The migration itself means extinction for many kinds which have specialized to the fatal extent that plasticity has been lost. The depth, the temperature, the clearness or turbidity, the kind of bottom, the kind of food, all must change, and if the ability of adaptation has been lost, all is lost! Of 10,000 species living just before one of these great breaks, only 300 appear in the reinvading seas. Ninety-seven per cent became extinct. Only the stress of the physical changes can account for such a faunal change. Thus the diastrophism, springing from interior changes in the earth, and determining the areas of land and water, the topography of the lands, and the areas of sedimentation and erosion, determines also great and rapid changes in the forms of life.

The paleontologist, therefore, conceives of two speeds in the evolutionary development of life. One of these is witnessed while physical conditions remain much the same. The other occurs when diastrophic disturbances alter the even tenor of the faunal ways, and is considerably more rapid.

Climatic response to the rhythm.—A very interesting feature of earth history is the record of revolutionary changes in climate. Of the most recent of these changes we are all aware. We know that the Great Lakes region, together with the northern part of the Ohio, the Mississippi, and the Missouri drainage areas, is smeared with a deposit of clay, sand, and gravel; unstratified, heterogeneously intermingled; that this rests on planed, grooved and striated surfaces of the bedrock, and that many of the contained bowlders are themselves planed and striated. We know that these phenomena are accepted as proof that the region was once covered by a continental ice sheet, similar to those of Green-

land and Antarctica today. This region now enjoys a much milder climate than it did a few tens of thousands of years ago.

Below the glacial drift of a part of the Great Lakes region we find the Niagara limestone, containing many splendid fossil coral reefs. In addition to being a record of a marine submergence of the region, this constitutes a record of a subtropical climate. Reef-building corals cannot live in water which cools below 68° F. The fauna of the Niagara limestone is known about Hudson Bay where there are very similar reefs, and even in Greenland, less than 9° from the North Pole. Not alone was the climate subtropical, if we may trust the evidence of the reef-building corals, but it also was non-zonal. Thus this geological record, taken as an example, tells of noteworthy climatic changes.

The earlier idea of climatic changes was a simple one, in harmony with the Laplacian hypothesis which postulated a molten condition of the early earth. Gradually, with a radiation of heat into space, the temperature was lowered and finally the first crust of the earth appeared. The solidified crust has grown ever thicker and thicker, and the climate ever cooler and cooler up to the present.

But this view is no longer accepted. In the sedimentary rocks overlying the oldest granites (the primitive crust of the older interpretation) and virtually at the bottom of the whole series of sedimentary deposits in North America, has been found a record of glaciation. According to the older view, the granitic crust at that time was still sizzling hot and the atmosphere contained the present oceans.

It is essentially correct to say that the stratigraphic history of the earth begins with glaciation and ends with glaciation. Nor is this all. In the billion years, more or less, of this history, there have been several glaciations (though the earth during most of this time has had mild, equable, non-zonal climates). One of these glaciations was even more remarkable than either the earliest or the latest. It saw glacial ice at sea-level in peninsular India, latitude 19° N., moving northward away from the equator.

Periods of glaciation have also been periods of aridity, as indicated by deposits of salt and gypsum. The earth today has great areas covered with glacial ice (Antarctica alone has an ice-covered area equal to half of North America) and there are still greater arid areas. Aridity and glaciation are extreme cases of the continental type of climate, as contrasted with the oceanic type.

If the earth today, with widespread, elevated lands and restricted ocean spread, is arid in places and glaciated in others, we should expect that similarly in the past, widely emergent continents should have been accompanied by glacial and arid climates. And we should expect the converse of this: the times of widespread seas and low, limited lands should have witnessed equable climates. When we examine the geological record, we find this to be the case. Glaciation and aridity have occurred during and immediately after the great diastrophic revolutions. The equable climates have prevailed during times of diastrophic quiet. The climatic variations seem to swing in unison with the gradational and diastrophic changes already outlined.

This can hardly be coincidence; it seems clearly to indicate causal relations. But varying extents of land and water alone do not seem adequate to explain the climatic changes. Dr. T. C. Chamberlin has advanced the hypothesis that variations of carbon dioxide in the atmosphere are responsible for these climatic oscillations and that such variations are due to diastrophism.

The significant items in the hypothesis are as follows:

1. Minerals of the deep-seated rocks are chemically unstable when exposed to the atmosphere and hydrosphere. Water, carbon dioxide, and oxygen enter into combination with their metals in the ordinary processes of weathering. Some decrease in the quantity of these constituents of the atmosphere and hydrosphere must therefore result. In the limestone and coal deposits in the lithosphere there is 30,000 times as much carbon dioxide as in the air today, and most of it must have been taken from the air during the geological past.

2. Carbon dioxide, at present constituting 3/10,000 of the weight of the atmosphere, is remarkable for its ability to prevent the escape of the long waves of the earth's radiation of heat, while permitting the shorter wave-lengths of the sun's radiation to reach the earth.

3. Diastrophic disturbances, such as occur at the end of geological periods withdraw the shallow seas into the deepened ocean basins, greatly increase the area and the altitude of the lands, uplift massive and lofty mountain systems, and thus expose much unweathered rock to the action of the atmosphere. The draft on atmospheric carbon dioxide through weathering, is then at a maximum and depletion should lower the average temperature in all latitudes. Cooler air will hold less water vapor, and water vapor is even more effective than carbon dioxide as a thermal blanketing agent. Thus the result of decreasing the carbon dioxide would be greatly multiplied. Lowering temperatures of the ocean would give them greater capacity for absorption of atmospheric carbon dioxide and the situation would become still more aggravated.

Our present-day climates conform to these conditions. We are living in one of these times of low atmospheric content of carbon dioxide, due to the extensive and elevated lands, restricted seas, and oceans of cold water, and immediately following or in the waning stages of a time of diastrophic adjustment in the body of the earth. To bring about a return to the equable, non-zonal climates which have prevailed during the earth's history, we must wait on two things: (1) the progress of the new cycle of erosion which will eventually lower the lands and thus check the abstraction of carbon dioxide through weathering, and will brim the oceans over on the continents and decrease the total land area; and (2) the cumulative effect of vulcanism which discharges carbon dioxide into the air and eventually makes good the loss sustained. Indeed, without vulcanism during earth history, it is highly probable that the atmosphere and the hydrosphere would long ago have lost their carbon dioxide and life on the earth would have come to an untimely end.

THE AGE OF THE EARTH

We have now reviewed very briefly the part played by the great geological processes during the recorded existence of the earth. One final question arises: "How long has this interplay been going on?" There are three kinds of evidence which lend themselves to the making of such estimates; the ocean salts, the thickness of the sedimentary rocks, and the radioactivity of the igneous rocks.

Ocean salts.—Water, flowing over and through the rocks of the land, dissolves material and removes it in solution to the ocean. Of all the substances dissolved in ocean water, sodium chloride alone tends to accumulate. All others enter into detrital or organic or chemical sediments. If we know the total amount of sodium chloride in the sea and the total annual contribution by streams, it is obvious that division of the larger figure by the smaller would express in years how long the process has been going on; that is, the age of the oceans and the length of time recorded in the sedimentary rocks. But there are several uncertainties in this method. The mean area of lands in the past probably has been considerably less than that at present. Stream gradients and, therefore, vigor of search for soluble substances have not always been those of the present. Sodium chloride in the ocean may have come, in part, from rocks of the shoreline and from rocks beneath the oceans. Some sodium chloride has been precipitated out of ocean water in the past and now constitutes our rock salt beds. And there are other qualifications not presented here. Evaluating these variable factors as best we may, the different computations give in round numbers one hundred million years for the age of the oceans.

A safer plan seems to be to base the computation on the unchloridized sodium now being contributed from areas of igneous rocks and to assume that the union with chlorine occurs after the sodium enters the sea. Most of the chlorine in the salt apparently has not come from leaching of rocks, anyway. We assume that this chlorine has come from volcanic gases. Computing

on the basis of unchloridized sodium, the stores of sodium chloride now in the oceans would demand 180,000,000 years for their accumulation. This method also is open to some of the objections to the preceding method.

Thickness of sedimentary rocks.—Apparently one of the simplest methods of estimating geological time is to take the total observed thickness of all geological systems now exposed, and to divide this by the rate at which the strata have been deposited. There is no great difficulty in getting the figures for the maximum thickness of all sediments now exposed. An estimate a little larger than the average calls for about 70 miles. Of course this is not all in one place any more than all the shingles on a roof are piled up in one place. But the rate of sedimentation—there's the rub! Sedimentation near the mouth of large and active rivers must be much more rapid than along coasts without them. Sedimentation near shore must be much more rapid than far from shore. Sedimentation in the accumulation of a limestone must be much slower than in deposition of a fragmental rock. Nothing better than a rough estimate can be used for our problem, and this will vary with the personal equation of the computer. An average of several estimates is one foot of sediment (weighted in terms of the relative abundance of the different kinds in the stratigraphic column) in 880 years. This demands 300,000,000 years since the beginning of an adequate sedimentary record.

But what of the unconformities which are present in the sedimentary series? The torn-out pages of the book of earth history? The duration of the periods of erosion, recorded by unconformities is unknown save that they were long enough for notable biological changes to occur and for extensive peneplains to be eroded.

Furthermore, the sediments which we examine and whose thickness we measure were deposited in the shallow seas on the continental shelves. During times of widespread emergence of the continents, detritus from the lands has gone off the edge of the platforms into the abyssal depths and is now inaccessible. Its thickness is unknown. Any estimate of the duration of geological

time from a study of the sediments must, therefore, be greater (possibly much greater) than the 300,000,000 years before noted.

Radioactivity.—Radioactive substances are derived from uranium and thorium minerals, constituents of the body of the earth. Each of these elements slowly and regularly breaks down and helium is continuously and lead is eventually produced. It is estimated that a given quantity of uranium will disintegrate to half the original amount in 6,000,000,000 years. If we have an igneous rock which contains uranium and helium and lead, and if all the lead and helium present are the product of the disintegration of uranium, and if all the lead and helium produced by this disintegration are still contained in the rock, the age of the rock may be computed (that is, the time since the igneous magma solidified and crystallized.) Igneous rocks have been formed at various times in the history of the earth. Since they contain no fossils, their age in terms of period and era must be learned from their relations to the fossiliferous sediments. If we can learn this and also can date them in years since crystallization, we can say how long ago such and such a period occurred.

Not many reliable computations on the basis of uranium decomposition have yet been made, but nearly all thus far made possess the right relative values. As to actual figures, the two geologically oldest granites studied appear to have crystallized from a liquid condition 1,125,000,000 and 1,500,000,000 years ago. The error inherent in this method is estimated not to exceed 20 or 25 per cent.

Question has been raised, however, as to the trustworthiness of our data on the rate of decomposition of uranium in rocks under great pressures and temperatures. The rate may have been considerably slower than it is in rocks at the surface. Computations based on radioactive decomposition of thorium have yielded much lower figures, but again there is question as to the adequacy of our present knowledge for such purposes. At any rate, the order of magnitude is correctly indicated and comparative time

values are more important in geology than statements of duration in years.

The attitude of the student of earth history is at once humble and exalted. The earth during inconceivable eons of time has passed through tremendous, but orderly, physical changes. An exceptionally delicate balance of conditions has made it a habitable globe. Living forms have suffered or have profited by these changes. Man, one of these living forms, has made a very late appearance in the drama. He is the only organism which is conscious of a past, which can reconstruct the events leading up to his own time, and, therefore, can understand in some measure where he belongs in the world-order. Man knows today that the earth is not anthropocentric (despite widespread belief that it is), and that affirmation of that belief cannot make it so. The scientific temperament; the desire to know for the sake of the truth, is as truly reverent as any acceptance of tradition. Our modern enlarged conceptions of the Nature of the World and of Man, properly considered, are sources of profound spiritual inspiration.

SELECTED REFERENCES

1. T. C. Chamberlin and R. D. Salisbury, *College Geology* (Henry Holt & Co., 1909).

2. H. F. Cleland, *Geology, Physical and Historical* (American Book Co., 1916).

3. J. W. Gregory, *The Making of the Earth* (Henry Holt & Co., 1912).

4. Arthur Holmes, *The Age of the Earth* (Harper & Bros., 1913).

5. Walter Libby, *The History of Science* (Houghton Mifflin & Co., 1917), chap. x.

6. F. A. Lucas, *Animals of the Past* (American Museum Handbook, 1922).

7. R. S. Lull, *The Evolution of the Earth*, chap. ii by Schuchert (Yale University Press, 1918).

8. W. J. Miller, *Introduction to Historical Geology* (D. Van Nostrand Co., 1922).

9. L. V. Pirsson and C. Schuchert, *Textbook of Geology* (Wiley & Sons, 1924).

10. H. W. Shimer, *Introduction to Earth History* (Ginn & Co., 1925).

CHAPTER IV

ENERGY: RADIATION AND ATOMIC STRUCTURE

HARVEY BRACE LEMON

INTRODUCTION

The unified character of modern physics.—A historical survey of the science of physics reveals as perhaps its most significant fact the evolution of this field of knowledge with respect to an ever increasing correlation of material not obviously related. Take, for example, the classical subdivisions of the science into mechanics, heat, sound, light, electricity, and magnetism. These terms were formerly regarded as referring to distinct and almost entirely unrelated aspects of material phenomena.

It has been found, however, that heat can be most readily interpreted in terms of mechanical laws. The phenomena of sound similarly find a most satisfactory explanation in the mechanical vibrations of material objects whether in the gaseous, liquid, or solid states. Electricity, furthermore, when in motion, has been discovered to possess magnetic properties; and moving magnets, conversely, can cause electrical currents. In such experiments mechanical forces are brought into play upon both the magnets and the conductors carrying the current. So it results that under the title of "electrodynamics" there are brought together the three originally distinct fields of electricity, magnetism, and mechanics.

Light, the ultimate nature of which is still a mystery, was first interpreted in a purely mechanical way, but subsequently, through the classical work of Clarke Maxwell, was shown also to be of electromagnetic character and consequently also was brought into the realm of electrodynamics. Finally, within the last thirty years, matter itself has been found to be essentially an electrical manifestation.

Now it is with respect to the more fundamental aspects of the nature of matter that modern physics is chiefly concerned. Rather than subdivide the subject into the usual now merely conventional divisions of mechanics, heat, sound, etc., because of the now largely unified character of all of the material, we shall deal, first, with light and allied phenomena under the name of "radiation," through the medium of which the nethermost confines of space are rendered accessible to us. Second, we shall discuss those particular aspects of electricity to which we owe our current ideas as to its nature and its relation to matter and atomic structure.

Before going into this, however, it will be well to observe in passing the close relation of physics to the other natural sciences.

Relation of physics to the other sciences.—The close connection of physics to other fields of scientific work is due to the fundamental character of its subject matter, and can hardly be overestimated. A large branch of modern astronomy calls itself "astrophysics," and between the domains of physics and chemistry all save artificial distinctions have vanished. These and other sister-sciences share her tools and methods in working on their most fundamental problems. The modern telescope could teach us but little about the nature of stars and galaxies were it not for the spectroscope attached thereto. The pivoted lever that forms the analytical balance of the chemist probably is the most important single tool by means of which curious human beings have ever pried into the Pandora box of nature.

Animal and plant physiologists use the delicate D'Arsonval galvanometer of physics; pathologists, the more modern types of vibration galvanometers in the study of the living heart. X-ray methods of diagnosis and treatment are standard in every hospital. Radio engineers have, with vacuum tubes, established a new technique in the study of diseases of the ear. The biologist discusses the activities of simple cells in terms of surface tension and osmosis, invents electrochemical models of living nerves, and in the recondite process of cell reproduction by division, discovers structures strikingly resembling electric and magnetic fields.

The far horizons of physics.—Physics, however, is not chiefly concerned with applications, nor with directly benefiting society, which perhaps already is in possession of more godlike powers than it can intelligently wield. The science of pure physics has been called forth in response to an overwhelming curiosity among a certain few of mankind as to the nature of the world. To many it may seem as if the results of these labors are of the stuff of dreams. Physics extends its inquiry even to the far-flung horizons of astronomy—perhaps beyond—into the nature of the atoms of which stars are made. Through eons compared to which the record of the rocks is but a fleeting moment we strive to trace the disintegration and synthesis of matter, paralleling the growth and decay of stars. Within an atom may be traced sequences of events so rapid that in comparison our brief span of human life assumes the stretch of a geologic age. Our human proportions also become of galactic magnitude when compared with such minutiae as atomic structures involve. Thus the vistas are equally dizzy toward the stellar systems in outer space and toward the atomic systems in inner space. It was thought only a few years ago that, as individuals, these atomic systems were no less inviolate than a nebula from human meddling. Recently, however, we have learned how to disintegrate some of them, and it may well be that the synthesizing of others is not far distant. Thus are two aspects of physics ever apparent; its theories lead always to new experiments—the gossamer substance of its dreams becomes embodied in the steel and brass of mechanism.

RADIATION

Energy.—In everything that we see in the world around us we recognize manifestations of what we call energy. In a lifted weight or a stretched spring we have examples of this energy in potential form. Its total amount is measured by the product of the force involved (here the pull of gravity on the weight) and the distance through which it has been active. There is another type of energy, which we call kinetic, possessed by an object

whenever it is in motion. A flying ball, a coasting automobile, possess kinetic energy. Likewise, here, the measure of energy in this form involves the product of two elements: the mass (or inertia) of the object and half the square of its velocity. The ever unavoidable friction which ultimately brings all motions of objects on our earth to rest illustrates the transformation of energy from this kinetic form into heat. This change, however, into what seems to be something quite different is more apparent than real, for a more searching analysis of the phenomenon of heat reveals that it is nothing more than a manifestation of the kinetic energy of the minute particles, called molecules, of which all matter is composed.

Mass.—We have defined kinetic energy as half the product of the mass of an object and the square of its velocity. The ultimate nature of this attribute of material things called mass is still conjectural. For all ordinary purposes of life, however, we use its most obvious property as a definition: all objects on our earth have *weight.* It is against the force of the earth's attraction that we do work, that is, use up energy, when we lift a weight through a given distance. Masses are defined by comparison of their weights with the weight of one arbitrarily chosen standard of mass.

Mass has a second important physical property which we call inertia, meaning thereby its resistance to any alteration of velocity in direction or amount. It is the inertia of a motor car that has to be overcome by the engine to get it under way; hence the gear shifts, needed only in starting, when the road is level. The brakes likewise are necessary to overcome the inertia so as to reduce the velocity quickly. Masses may be measured equally well by comparison of their respective inertias as well as of their respective weights.

The third, less obvious, property of all bodies that we can handle and experiment upon is that they exhibit an attraction for one another. It is the attraction of the vast mass of the earth, called gravitation, that gives weight to all objects on its surface,

and indeed reaches out across the deeps of space and holds the moon, as if tied by a gigantic but invisible cable, whirling round our planet like a stone in a sling. By means of very delicate balances even the attractions of bodies of a few hundred pounds weight for still smaller ones can be measured. It is with the multitudinous interrelations of material objects involving their masses, velocities, forces, momentum (product of mass and velocity), and with transformations of energy, both potential and kinetic, that the technical and engineering aspects of physics, and especially that branch of it known as mechanics, largely deal. This subject naturally forms the beginning of any detailed study of the science, but in this brief discussion we can pursue it no farther.

Sound waves.—An important characteristic of many manifestations of energy is the fact that it is transferred from the region of space in which it originates to others far remote. When we strike a bell, we set its rim into vibration. This vibration is communicated to the surrounding air and, because of the elasticity of the air, this vibrational energy is handed on with great rapidity into regions more and more remote, spreading out in all directions and gradually, because of this and friction, diminishing in intensity.

Our sense of hearing enables us to detect over 11 octaves of vibrations ranging from the vicinity of 32 to 32,000 per second. These waves vary in length from 35 feet to about $\frac{1}{3}$ inch. Inaudible waves much longer or shorter than these can be produced, of course. Such waves, inaudible to man, may be audible to other animals. For example, a dog can hear sounds considerably more shrill than the upper limits of human audition. Some insects seem equipped for producing, and seem to hear, sounds of even higher pitch.

Waves of all sizes travel with the same speed—fortunately indeed, since otherwise music would become greatly confused if heard from a distance. This speed varies from about 1,100 feet per second in air to 5,000 in water and 15,000 in hard metals, such as steel. Sound waves, such as we have been describing, require always a material medium for their propagation. Sound cannot

traverse a vacuum; and yet there are many other forms of energy that can, and it is with these others particularly that we shall deal under the name of radiation.

Light waves: their sizes and velocity.—In the world of nature light plays the rôle of a great revealer in many ways unsuspected save by those whose curiosity has led them to delve deeply into its study. So complex is the design of light that it not only makes clear to us the superficial nature of the objects which it illuminates, but it carries, woven into the warp and woof of its gaily colored patterns, most intimate details concerning the nature of

TABLE II

Kind of Waves	Lengths
Long electromagnetic.........	Hundreds of miles to 15 miles
Wireless telegraphy...........	15 miles to ¼ mile
Wireless telephony	¼ mile to 120 feet
Short electromagnetic.........	120 feet to $\frac{1}{100}$ inch

	In Scientific Units				In Decimal Fractions of an Inch	
Heat...............	300.	to	.7	μ*	.01	to .000,028
Visible light.........	7,000.	to	3,500.	A.U.*	.000,028	to .000,014
Ultra-violet.........	3,500.	to	130.	A.U.	.000,014	to .000,000,5
Indirect methods....	130	to	45.	A.U.	.000,000,5	to .000,000,17
X-rays.............	45,000	to	100.	X.U.*	.000,000,17	to .000,000,000,38
γ-rays...............	100.	to	5.6	X U.	.000,000,000,38	to .000,000,000,02
Cosmic rays........	.67	to	.4	X.U.	.000,000,000,002,6	to .000,000,000,001,5

* 1 μ = 10^{-4} cm. 1 A.U. (Angstrom Unit) = 10^{-8} cm. 1 X.U. (X-ray Unit) = 10^{-11} cm.

its origin, whether that origin be a distant nebula or the feeble flicker of a firefly. Now the reason that much of the information carried by light is not at once apparent to us is because our eyes are totally blind to the messages that radiation brings except for one small octave of its colors. Over a vast scale of radiant waves —the longest measured in miles, and the shortest in hundred thousand-millionths of an inch—covering as many as 55 octaves, we can see but one. Our information about all the others must be obtained by instruments constructed to record these invisible radiations and to translate them into the limited visible or auditory regions of sense impression. Table II classifies the various radiations which we recognize and study, and in it is seen the vast difference in the sizes of the waves involved.

The enormous range of scale involved even in the latter part of Table II can be better appreciated if we imagine the entire range magnified so that the longest heat waves, actually 1/100 of an inch, are increased to 43,000 miles so that one of them would nearly twice encircle the earth!

Then we should have the following relations:

Heat	43,000. miles	to	100. miles
Visible light	100. miles	to	50. miles
Ultra-violet	50. miles	to	2. miles
Indirect methods	2. miles	to	3,700. feet
X-rays	3,700. feet	to	9. feet
γ-rays	9. feet	to	5. inches
Cosmic rays	about ½ inch		

Visible light is limited to a narrow range of one octave. Going toward shorter waves, we discover that a photographic plate is able to "see" wave-lengths very much shorter than are visible to the eye, in the region that we call the ultra-violet. Many insects, indeed, are sensitive to, that is, see into the ultra-violet region of the spectrum farther than do we. The most transparent forms of matter, such as glass or quartz, however, are opaque to these short waves,[1] and the region between 10 millionths and 1.3 millionths of a centimeter can be studied only by means of apparatus through which the light travels entirely in a vacuum, the limpid air itself absorbing this region completely. Curiously enough, to still shorter waves, that we call X-rays, matter is again highly transparent, and materials that are opaque to light transmit these extremely short waves comparatively well. Below the shortest X-rays, still generally known as gamma (γ) rays, there are other waves, called cosmic rays, since they originate in a manner yet unknown in the depths of space outside the earth. They have been investigated only very recently, with respect to their size, and are found to be extraordinarily minute, the distance

[1] This opacity is caused by the power which radiation possesses of partially tearing apart the atoms on which it falls. The energy so absorbed is transformed in a variety of different ways.

from one wave to another being 5 trillionths (.000,000,000,005) cm., a distance ten times smaller than the corresponding dimensions of the shortest γ-rays. Millikan is of the opinion that these waves come in upon our earth uniformly from all directions of external space, signals of mysterious phenomena taking place in the universe around us about which we can at present only speculate.

The velocity with which visible light and all of these many other radiations of greater and shorter wave-length is propagated, as far as we can determine, is the same for all. It has been measured most accurately in the visible region by Professor Michelson. Since it travels with the prodigious speed of no less than 186,300 miles per second, the determination of its velocity is an experimental task of great difficulty. It was solved by reflecting a powerful beam of light from a mirror which could be driven at a very high speed of rotation. This beam of light at a certain position of the rotating mirror is projected to a distant mirror about 20 miles away. During the time occupied for its journey there and back, the rotating mirror moves through a small angle, after which, receiving the returning beam, it reflects it to a position different from the one at which it originated. Measurements of this displacement, and of the corresponding speed of rotation of the mirror, together with the distance traveled by the light to and fro, enable us to calculate the velocity.

Refraction and dispersion of light.—Light waves of different lengths travel with the same velocity only in a vacuum, for when light encounters in its path any transparent material medium, then its velocity becomes dependent upon its wave-length.[1] If a beam of light falls upon a prism of glass in any direction except perpendicular to its surface, it is bent toward that perpendicular direction. This effect we call refraction. The bending is caused by the fact that different colors (wave-lengths) travel with different velocities in the glass, and all of them with velocities less than

[1] The air, of course, is to a certain extent such a medium; and determinations of the velocity of light through air must be corrected in order that we may obtain the velocity in a vacuum.

their common velocity in a vacuum. Different colors, consequently, are bent in different amounts (Fig. 16). By way of illustration we can see the same phenomenon when one end of a long column of soldiers marching abreast encounters a patch of loose, sandy soil, lying obliquely across its line of march. That end becomes slowed down, and if the line of march is always perpendicular to the line of the rank, the column will be deflected toward the sandy patch. This corresponds precisely to refraction, the direction of march being the direction of the beam of light, and the line of the rank perpendicular to it representing what is known as the wave-front of the beam. By dispersion is meant that different wave-lengths are bent differently, the longer waves less than the shorter ones, just as soldiers with long legs might be less impeded by the sand than companions who, because of shorter stature, could not take so great a stride. Thus there would be a sorting out by the sand of men of different leg-lengths, who, in time, would fan out into different directions, the shorter ones traveling more obliquely to the initial direction.

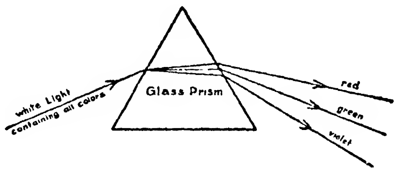


FIG. 16.—Separation of white light into different colors by a prism.

Spectra.—The separation of different colors into different directions by virtue of their different velocities furnishes us with a means of analyzing a beam of light into its constituent vibrations. The band of color so produced from white or any other complex light we call a spectrum.

There are other methods, in some ways more effective than the use of a prism, for analyzing light. The most important of these is by reflecting it from a polished plate of metal upon the surface of which are ruled with a fine diamond point many hundred thousand parallel lines, as close perhaps as 20,000 lines per inch. To produce such a surface having a uniformly spaced ruling is obviously a problem of almost insuperable difficulty. Such a ruled surface, known as a diffraction grating, separates a beam

of light into its elements for reasons altogether different from those upon which the action of a prism depends. The grating has the advantage of making a much finer analysis than can be made by a prism, but it requires a much more intense light, and hence is not so practicable with faint sources.

Any device which is equipped with either a prism or a grating, a narrow slit and a lens also being required, for the purpose of analyzing light is called a spectroscope. Since light has its origin within the minute molecular and atomic electrical systems of which all matter is composed, it is not surprising to discover that when analyzed into a spectrum it reveals an enormous amount of information about its source.

Continuous spectra and temperature.—Light from an incandescent solid filament or a molten liquid surface when passed through a prism is separated out into a band of colors which extend by continuous gradations from red through yellow, green, and blue to violet, and constitutes what is known as a continuous spectrum (Fig. 17, *A*). Such a spectrum, containing not only all wave-lengths throughout the visible region, but extending into the invisible infra-red and ultra-violet on either side beyond, is found to vary greatly in the relative intensity of its different portions. This variation of intensity in different wave-lengths is intimately connected with the temperature, that is, the kinetic energy of agitation of the molecules, of the source. Thus we are enabled, without the use of a thermometer, to determine the temperature of an incandescent body by analyzing the light that it emits. The spectroscope is thus able to reveal to us very definite information about the temperatures of stars that are hundreds of light-years distant. Temperatures of stars are found in this manner to range from about 2,500° to 25,000° C. Our sun has a temperature of about 6,000° C.

Bright-line spectra.—If the source of light is a gas instead of a solid or liquid, the spectrum which it emits contains only isolated portions of the continuous band of color, and is called a bright-line spectrum, illustrated in Figure 17, *B*. There is a remarkable definiteness about the positions of these bright lines

in the spectrum from any individual kind of atom or molecule. This is not surprising, since in a gas the atoms and molecules are quite isolated from one another, being from hundreds to many thousand times as far apart as the diameters of the atoms themselves. Consequently, the little electrical systems of which these atoms or molecules are composed (as we shall see later in more detail) are relatively undisturbed by one another and are free to oscillate for some time in their own natural periods. This time of freedom is not long, compared with human standards. In 1 second the sodium atom sends out 500,000,000,000,000 waves (5×10^{14}) in one wave-length alone. Now, although the gas molecules at atmospheric pressure on the average collide with, and consequently disturb, one another about 5,000,000,000 (5×10^{9}) times per second, they still are free long enough to send out 100,000 wave signals (1×10^{5}) without interruption; that is, $5\times10^{14}\div5\times10^{9}=1\times10^{5}$. At the much lower pressures at which the phenomena of radiation from gases are usually observed, the number of waves sent out without interruption might well be many hundreds of millions. Usually, however, the vibrations set up within the little systems die away long before such a result is attained.

Spectrum analysis.—The light emitted by a body enables us to ascertain something of the nature of its source, just as the sound emitted by a bell or vibrating string or tuning-fork or pipe enables us to recognize the character of the instrument emitting it. For example, hydrogen atoms give a spectrum which consists of a group of lines in the visible region, illustrated (Fig. 18, *B*) in the photograph taken of hydrogen in a laboratory source; Figure 18, *A* is the spectrum of a star, and, although on a quite different scale, it has the same lines and indeed many more.[1] Furthermore, a certain regularity becomes evident. Such regularities in the spectral lines exhibited by many elements are of great importance in enabling us to learn something of the structure of the atoms from

[1] In the stellar spectra the lines are dark on a bright background instead of bright. This is because the incandescent solid or liquid interior emits a continuous spectrum. The gaseous atmosphere alone would show bright lines but absorbs light from the interior in exactly those wave-lengths which it emits with the result that these regions appear dark by contrast. Such spectra are called absorption spectra.

which they originate. Hydrogen molecules, on the other hand, have an altogether different and much more complicated spectrum (illustrated in Figure 18, *C*) in a laboratory source. This spectrum, except for a few faint lines, is unknown in the stars, from which fact we conclude that hydrogen exists in stars as atoms rather than as molecules.

By means of the spectroscope we are, therefore, enabled to investigate the chemical composition not only of many substances in the laboratory, where of course other methods are available, but also of stars, comets, and nebulae, which are so remote that we can get this information in no other way.

The velocity of a source of light determined from its spectrum.—When we ride in a railroad train swiftly past a crossing where a bell is sounding, we all notice the curious falling pitch of the tone. This is due to the fact that as we recede from the bell the sound waves coming toward us strike our ears less frequently than they do when we are approaching it. The pitch falls in consequence. In order that this phenomenon shall be conspicuous it is only necessary that our velocity shall be an appreciable fraction of the velocity of sound, perhaps 50–100 feet per second. A similar phenomenon occurs in light. If a source of light is moving toward us, the waves strike our eyes with greater frequency than if it is moving in the opposite direction. This greater frequency, producing a correspondingly shorter wavelength, alters the color of the radiation slightly toward the violet on approach, and similarly toward the red on recession. Of course, this occurs only when the velocity of the source is not entirely negligible compared to the velocity of light. The latter is so very great that only in the motions of the atoms and the stars do we discover sufficiently high velocities to produce this effect. Once the effect is observed, however, its magnitude enables us to determine quite precisely the velocity in question. In this way, by measuring the slight displacements of spectral lines coming from atoms, either in the stars or in the laboratory, are we able to determine the component of their velocity that is along our line of sight.

The net result of a broad survey by means of the spectroscope into the chemistry of the universe around us is that we find this universe to be composed, with very few exceptions, of the same materials with which we are familiar in our own atmosphere and soil. There is a unity in it all that makes us feel quite at home in it. We find, also, that, on the whole, the myriads of stars are moving among one another with velocities comparable to that with which our solar system speeds through the galaxy, or at the rate of about 400,000,000 miles per year.

It is largely through the spectroscope that we have become aware of the discrimination between giant and dwarf stars. The former are thinner than air, but larger than our entire solar system. Our sun is a star of the dwarf type, but there are many different degrees of both dwarf and giant condition. These differences were first inferred solely from observations of stellar spectra and magnitudes, but subsequently they have received confirmation from other kinds of evidence, also optical, and borne in to us along the beam of radiant energy. The smallest and densest star we have so far found is the one that revolves as a faint companion around Sirius, the dog star. It is thought to be as small as the planet Uranus, of our solar system, and yet to have a mass comparable to that of the sun. The matter of which it is composed is thus of almost unimaginable density. If our conclusions are correct, a pint cup of the material of this star brought to the surface of our earth would here weigh 25 tons!

Stellar and atomic evolution.—It is an interesting fact that usually there is a systematic progression in the different chemical elements that put in their appearance one after the other as we pass from the spectra of the giant stars to those of dwarfs. The temperature is low in the former stars, and low again in the latter, but with a maximum of dazzling heat somewhere in between. At the highest temperature only the lightest gases (hydrogen and helium)—whose atoms we shall see are of the simplest type—are found in stellar atmospheres. In cooler stars the lighter metals make their appearance, and also other somewhat more complex

atoms. At stages of low luminosity, in the deep red stars, we find not only some of the much heavier elements, but chemical compounds as well, such as oxides of titanium.

Thus, while looking at and trying to piece together the vast history of stellar evolution—from giant stage to dwarf and back and forth—with some stars suddenly making amazing short cuts, events in the nature of accidents in their careers, we observe a similar evolution in the atoms themselves. Evolution within the atoms seems to run parallel to evolution in the stars. This guiding principle here seen but dimly as to detail, but definite as to main outlines, is majestic and inspiring.

In our recognition that order is universal, a fact confirmed by myriads of observations of patient, indefatigable, and devoted investigators, the old saying that "an irreverent astronomer is mad" can apply with equal force to the physicist. Man learns something of his own minute and colossal stature, and he comes to feel that his own intelligence, which enables him to make such sublime discoveries, is the supreme achievement of evolution.

ELECTRICITY AND MATTER

Beginnings of atomic theory.—In no field of modern science have more tremendous changes occurred in the last twenty-five years than in the subject of electricity. These changes have not been so much in the amplification of older points of view as in the discovery of new and totally unexpected phenomena, the existence of which was undreamed of before. It is said that great events often cast their shadows far in advance, and this is indeed true in this domain.

The eighteenth and nineteenth centuries of physics were very largely concerned with ideas of continuity. In the twentieth, the dominant note is atomicity. It is true that as far back as 400 B.C., Democritus, of Abdera, known as the Laughing Philosopher, conceived the idea that the material things that surround us are composed of minute and discrete particles. He saw in the wearing away of flagstones, in the drying of linen in a wind, in the disappearance of the salty taste of a solution upon dilution with pure

water, and in the subsequent recovery of the salt upon evaporation, manifestations of the atomicity of matter. But these observations were merely qualitative, and his ideas derived from them can be regarded only in the light of preliminary speculations. Twenty centuries elapsed before modern science, with its experimental method, began to prove the correctness of this opinion.

Modern atomic theory with respect to matter began with John Dalton, a Quaker schoolmaster in England, living between 1766 and 1844. In a subsequent chapter the reader will learn the details of the fascinating story of how the early experimental chemists discovered, by means of the relations of substances entering into chemical union, not only proof of the atomicity of matter, but quantitative measures of the relative weights of the various atoms and molecules. These atoms and molecules are the smallest parts into which material objects can be subdivided without alteration of the usual properties which establish their identity.

It was Mendeléeff who first formulated with great completeness a table of the elements, some eighty odd, of which all the myriad forms of matter in the universe around us are composed. When these elements were arranged in order of increasing weight, it was discovered that there is a curious rhythm in the list. Atoms having similar physical and chemical properties followed one another in intervals of the "magic" number seven so that if one broke the list with the seventh, and wrote the eighth under the first, the ninth under the second, and so on, the atoms occurring in various vertical rows of the table strongly resembled one another.[1] That things presumably fundamental in their character should show such relationships is an obvious challenge of their fundamental character, and the periodic table of the elements, as it was called, remained one of the most puzzling questions in chemistry almost up to the beginning of the twentieth century.

The kinetic theory of heat.—One of the most important achievements of the nineteenth century in laying a solid founda-

[1] This description does not take into account the recently discovered "Zero Group" of inert gas elements now included in such tables nor the fact that the rhythm changes after the twenty-first element.

tion for the towering structures of the twentieth to be reared upon was made by Joule, Clausius, Mayer, Kelvin, and a host of others, in interpreting experiments on the behavior of gases, especially with regard to the effects of temperature.

It is well known that the pressure exerted by gas upon the walls of its containing vessel varies inversely with the volume to which it is compressed, provided the temperature remains unaltered during the process (Boyle's law); also, that in case the temperature changes, the product of the pressure by the volume is proportional to this temperature, provided the zero of the temperature scale be chosen at approximately 273° C. below the freezing-point of water (Charles' law).

Joule and his contemporaries conceived a gas to be composed of isolated particles, perfectly elastic, which, bounding and rebounding from one another and from the walls of the containing vessel like billiard balls, occupied in this sense, and in this sense only, the entire space within the vessel. The temperature is merely a manifestation of their average kinetic energy of agitation. The pressure exerted on the wall is due to the sum total of the innumerable impacts which the particles individually make upon it, and is measured by the total change in momentum imparted every second to the walls. Decreasing the volume of the vessel increases the number of molecules in every cubic centimeter (the density), and consequently, in the same proportion, the total number of impacts, that is, the pressure.

For purposes of simplicity, in these early formulations, molecules were supposed to be geometrical points and quite without effects in the nature of attraction upon one another. Subsequent experimentation showed that the laws of Boyle and Charles are not exactly true, but that there are definite departures from the simple relations, systematic and regular and much larger than the errors involved in later and more refined methods of experimentation.

The development of a theory.—The kinetic theory illustrates the way science always progresses. A hypothesis is formed in the endeavor to interpret a comparatively small group of newly ob-

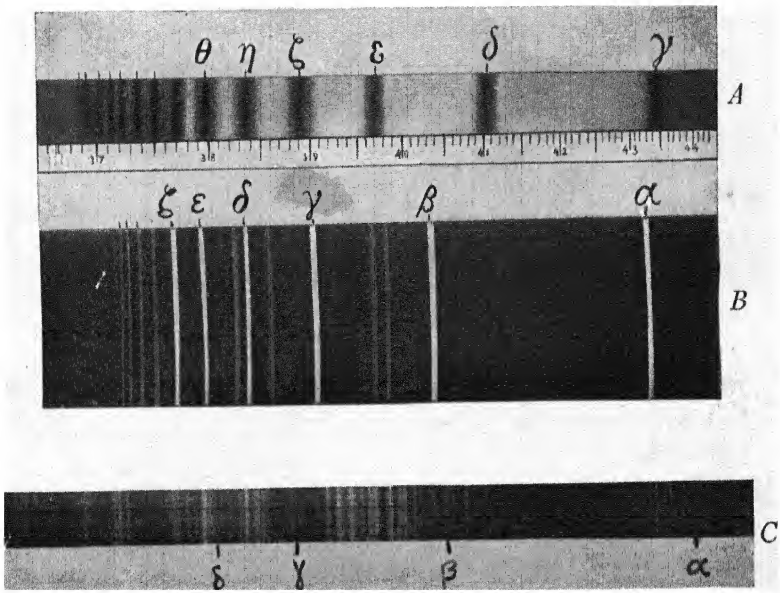
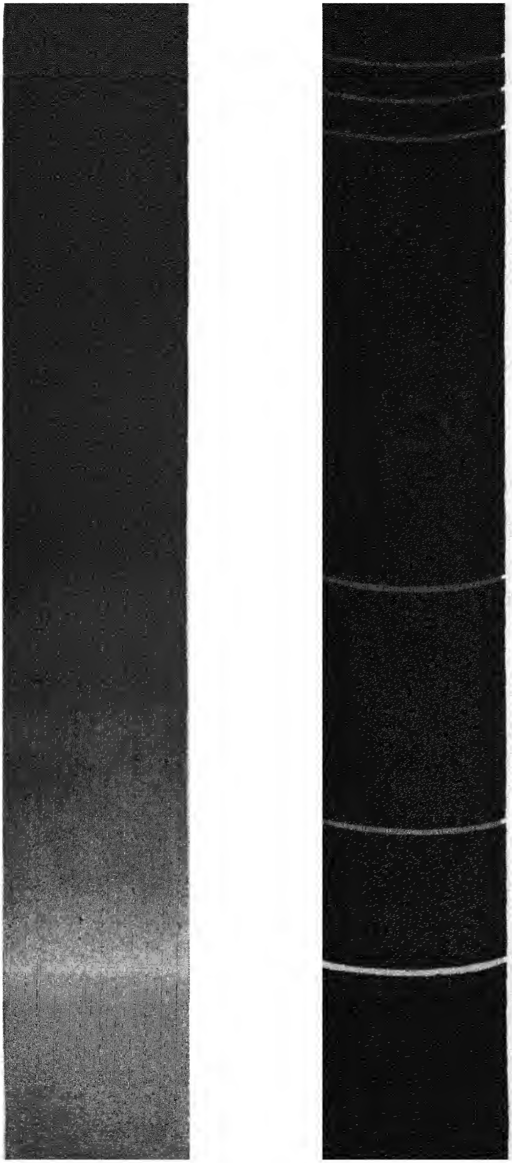


FIG. 18.—Hydrogen spectra in stellar and laboratory sources



A B

FIG. 17

served phenomena. Subsequent improvement of technique almost invariably discloses the fact that the phenomena are not quite so simple as was originally supposed. Now it is not a very rigorous test of a hypothesis that it fits the group of facts for which it was designed. This is a test merely of the ingenuity of its inventor. But when it is found that the original set of facts must be radically modified as a consequence of subsequent discovery, then one of two things must be done to the hypothesis: either it must be thrown away altogether and a new one invented, or else it may be that slight alterations in the way of natural and unforced additions to the primitive hypothesis may enable it, thus modified, to account for the subsequent and more precise delineation of the phenomena in question. Then does the hypothesis become more than a useful working tool, and begin to carry conviction as to its expression of the elements of truth.

In the case of the kinetic hypothesis, it was shown by Van der Waals that it is only necessary to assume, reasonably enough, that these molecules are of finite dimensions, and, provided they are sufficiently close together, that they exert slight attractive forces upon one another, in order to make the picture include quantitatively not only the approximate laws of Boyle and Charles, but also the systematic departures from them that are observed. The equation developed by Van der Waals in this connection led to certain unforeseen results, namely, that by the amount of departure in a given gas from the laws of Boyle and Charles one could be led to certain definite and quantitative expectations regarding temperatures, pressures, and volumes at which liquefaction of the gas in question would take place. Thus new types of experimentation were not only suggested, but the results that would be obtained were indicated in advance. In this particular case when the experiments were performed, the predictions of the theory were amply vindicated.

Thus it appears that we may be led to the discovery of new facts not only by direct experimentation, but also through the somewhat mysterious rites and rituals of the symbolism of pure

mathematics. In this fact alone would mathematics as a leading science find ample justification in the mind of the experimental investigator—were such justification at all necessary.

In this way did the kinetic theory pass from the early stages of speculation and hypothesis into the dignity of a universally accepted point of view with respect to the atomic characteristics of matter, containing interpretation of temperature as nothing more than a manifestation of kinetic energy of molecular agitation. Like the Copernican theory of the solar system that places the sun, and not the earth, at the center, first appearances to the contrary notwithstanding, or the theory of Pasteur that many diseases are caused by micro-organisms and may be controlled more readily by the study of the life-history of these tiny plants or animals than by religious ceremonials—thus did the kinetic theory of heat toward the close of the nineteenth century find a correspondingly secure place in the minds of scientists. Nor has anything occurred in the tremendous strides forward which have been made in the last twenty-five years to lead us to believe that this theory, essentially unchanged, will not remain an integral part of the vast structure of all scientific thought for time to come.

Early notions of electricity.—The subject of electricity has a distinctly modern flavor. Our own Benjamin Franklin (1706–90) was the first to make any real contributions to human knowledge in this field. It was he who showed clearly by experiment that there are two kinds of electricity, that which appears on glass when rubbed by silk, which he chose to call "positive," and that which appears on sealing wax when rubbed with fur, which he called "negative." We recognize that the negative also appears on the silk, equal in amount to the positive on the glass. The corresponding thing is true of the positive on the fur. Now, like kinds of electricity repel each other and unlike kinds attract. The forces that are involved are proportional to the amounts of electricity involved, and they decrease as the square of the distance between the charges increases. This law is exactly similar to Newton's law of gravitation. The unit electrical charge is defined as

that which, when placed one centimeter from a precisely similar charge in air, repels it with unit force (one dyne).

The electrical current which flows from a battery was not at first recognized as being merely another mode of manifestation of the electrical charge discussed above, but we now know that it is nothing more or less than manifestation of the motion of these charges, traveling with considerable speed through that class of materials, the metals, that are known as conductors of electricity. When a unit quantity of electricity flows through a conductor in a unit of time, we say the conductor is carrying a unit current, quite as we should define the current of water through a pipe by measuring the amount that flows out in a given time. This analogy caused the early workers in electricity to regard it as a fluid, and this idea is still reflected in the fact that modern electrical engineers still refer to electricity colloquially as "juice."

Franklin, however, clearly recognized the possibility of electricity being of atomic character, for he said "the electrical matter consists of particles extremely subtle, since it can permeate common matter, even the densest, with such freedom and ease as not to receive any appreciable resistance." Franklin had no proof of this, any more than Democritus had of the existence of ultimate particles or atoms of matter. The notion was frankly speculative. It was Faraday (1791–1867) who found the first experimental evidence of the atomic character of electricity in studying phenomena associated with the passage of electricity through certain solutions that readily conduct it, known as electrolytes. He discovered that the amount by weight of substances removed by deposition on the electrodes or released in their vicinity as gas by the passage of electricity through such a solution depends, first, only upon the total quantity of electricity which passes through it. A strong current for a short time produces the same effect as a weaker current for a corresponding longer time. In the second place, when the same quantity of electricity passes through different solutions, the weights of material separated out are proportional to the relative weights of the atoms and molecules of the

substances in many cases. In all other cases these weights are as closely as we can measure one-half, or one-third, or one-fourth, the relative weights of the atoms or molecules involved. The denominators of these fractions, moreover, are the same numbers as those associated with the chemical properties of the corresponding atoms and molecular groups under the name of "valence," which will be discussed in detail in chapter v.

Faraday's work compelled the conviction that one certain definite quantity of electricity must be associated with many different chemical atoms, and furthermore, that all the others must have associated with them simple integral multiples, such as two, or three, or four times this quantity. Thus the existence of a fundamental electrical charge is inseparably connected with the fundamental relations of chemistry.

Conductivity in gases.—During the latter part of the nineteenth century, it was discovered that under certain circumstances gases, ordinarily nonconductors of electricity, become conductors. The pioneer work in this most important modern field, and many of the important and far-reaching conclusions drawn from it, are due very largely to Sir J. J. Thomson, of the Cavendish Laboratory, in Cambridge, England.

If an electroscope, which consists of a light leaf of metal foil hanging freely beside a rigid vertical metal plate to which it is attached at its upper portion, be charged, this charge, distributing itself equally on foil and plate, causes the former to be repelled from the latter so that it stands out from it at an angle which may approach 90°. Now, if the gases from a flame such as a match or Bunsen burner be brought into the vicinity of this electroscope, the charge rapidly leaks off and the leaf collapses. This is found to be true whether the electroscope is charged positively or negatively. It shows that there exists in the gases from the flame both positively and negatively charged particles, one or the other of which, attracted either by the negative or positive charge on the electroscope, is drawn to it, and thereby neutralizes the charge and causes the leaf to collapse. Indeed, if a positively charged plate is placed in a tube opposite a negatively charged one, and

gases from a flame are passed between the two, the simultaneous migration of positively and negatively charged gas particles to each can be observed. Of course, if there are no charged objects in the vicinity of these products of combustion, the charge produced in the process quickly disappears because the positively and negatively charged particles then seek out and neutralize one another.

These charged particles must be some of the molecules themselves, for the most painstaking search has never revealed any mysterious stranger present to which these temporary electrical effects can be ascribed. Furthermore, the mechanism of conductivity of gases bears such strong resemblance to that of solutions, long since interpreted in terms of charged atoms and atomic groups, that the same terminology has been used for both. The charge-carrying atoms or molecules are given the name "ions" because of their nomadic tendencies, in which they follow of course the laws of electrostatic attraction stated in a preceding paragraph. The charge which these ions carry in gases is never smaller than the smallest one carried by ions in the electrolysis of liquids. In the case of gases not only this unit charge, but also every integral multiple of it, up to several hundred, has been found and measured. On the other hand, no charge has ever been observed into which this unit charge cannot be divided and leave no remainder. The first direct measurement of this unit charge, free from those statistical considerations that in earlier investigations gave only the average value and assumed rather than proved that individual values were all alike, was made by Millikan in 1910. These investigations put on a sound experimental basis a new atomic theory, the atomic theory of electricity.

A charged body is thought of as having the electricity distributed uniformly, as spots, peppered as it were, over its surface. The flow of electricity through a conductor, as we have seen, is thought of as a migration of these minute electrical atoms, through the conductor. However, as yet we have discussed no evidence which shows that these atoms of electricity can be divorced from the atoms of matter with which they are almost al-

ways associated. Have we evidence of their existence as independent entities? The answer can now be made in the affirmative.

Electrons.—Simultaneously with the discovery of gaseous ionization and the recognition of the similarity of this process to conductivity in liquids, experiments of other types during the latter part of the nineteenth century, and the opening decade of the twentieth, began to give independent testimony as to the atomic nature of electricity. Thomas A. Edison in the early days of his work in connection with evacuated incandescent lamps discovered that if an insulated wire is sealed through the glass bulb of a lamp, as illustrated in Figure 19 at *A*, and if this wire is connected through a galvanometer, *G*, to that side of the filament which is connected to the positive end of the battery, *B*, which heats the filament, *F*, a current will flow through the highly evacuated region between the filament and the insulated wire, indication of which is given by a deflection on the galvanometer. This current appears only after the filament has been heated above a certain temperature, after which it increases very rapidly with the temperature. No such flow of current, however, takes place if this wire is connected to the negative terminal of the battery. Obviously such an effect could be explained by the assumption that at a sufficiently high temperature negatively charged particles evaporate from the filament and are attracted across the intervening space by the positive charge on the wire connected to the battery. That particles carrying only negative

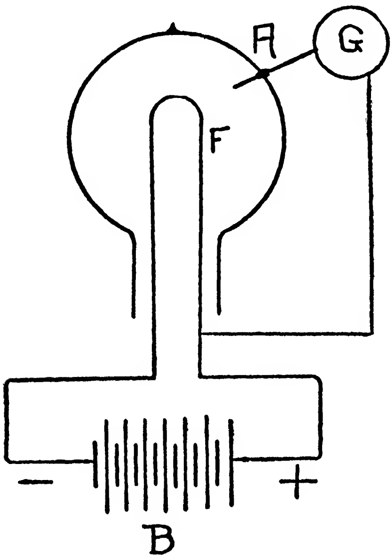


FIG. 19.—The thermo-electric flow of negatively charged particles.

charge are evaporated from the wire is proved by the fact that if the wire is made negative instead of positive no current appears. This is a marked contrast with the facts of gaseous ionization, in which charges of both signs are always found to be present. Furthermore, the effect we have just been describing is most definite only when the incandescent lamp bulb is pumped down to a very high vacuum, so high indeed that the residual gas remaining in it may be entirely neglected. One recognizes in these experiments the primitive beginnings of the modern radio tubes which have recently become a conspicuous element in our life. The phenomenon is sometimes called the "thermo-electric effect."

Another very similar discovery made in the late eighties was as follows: If a freshly polished zinc plate be placed inside of a bulb exhausted to a very high vacuum, and connected to a sensitive electroscope charged negatively, the electroscope will be discharged at once, provided a beam of ultra-violet light is allowed to shine upon the plate through a quartz window in its vacuum chamber. On the other hand, if the plate is charged positively, no such discharge under the influence of light can be produced. This again has been interpreted by assuming that in some way negatively electrified particles are released from the plate by the action of ultra-violet light. When the plate is negatively charged these particles on being released are repelled away from it, the negative charge leaks off, and the electroscope leaves collapse. On the other hand, if the plate is positively charged, negative particles, although released by the light, cannot leave the plate to which they are firmly held by the positive charge upon it. If originally uncharged, the plate, under illumination, acquires a positive charge due to the leakage from it of some negative charges released by the light which continues until the residual positive charge remaining prevents the loss of any more negative. This phenomenon is called the "photo-electric effect." By a long series of experiments on the thermo-electric and photo-electric effects, these streams of negatively charged particles have been isolated. It has been established that it is their motion that causes the current through the evacuated regions they traverse. Quite like

electric currents in a wire, they can be deflected by means of a magnetic field. They can also, obviously, be deflected if made to pass between two parallel plates which are charged, one positive and the other negative. By combining this latter electrostatic deflection with the magnetic one, it has been possible definitely to prove the negative character of the charge, and also to measure not only the velocity of the particles but their masses as well.

In connection with this measurement of the mass of these electric particles an astonishing result was obtained in the discovery that they possess a mass which is only 1/1845 part of the mass of the lightest known atom—hydrogen. Furthermore, whether these particles, which are called "electrons," have their origin in filaments of carbon, or platinum, or iron, or tungsten, or are released by the action of light from plates of zinc, magnesium, or copper, or from such metals as sodium or potassium, they are, as far as our measurements can determine, with respect to charge and mass, absolutely alike. Their velocity of emission, ranging from a few to many thousands of miles per second, for the most part depends solely on the strength of the electrical field with which they are pulled, and their mass is in no way connected with their origin. They are recognized as identical in magnitude of charge with those electrical atoms associated with material atoms in the conductivity of electricity through solutions and through gases, and they constitute the answers to the question raised in a preceding paragraph (p. 106). Because of the divergent ways in which they can be obtained from all sorts of substances, as well as for a variety of other reasons, they are also recognized as being, in part, the building blocks of matter. With their discovery and identification in this manner, a flood of light was poured upon the foundations of chemistry and the mystery of the periodic law was solved. With increasing atomic weights of atoms more and more electrons are involved in their composition. As these electronic structures are built up with more and more complexity, as we shall see later, certain features in their structure have been found periodically to recur, and it is these features which are re-

flected in the periodic changes of the physical and chemical properties of the elements. Characteristics hitherto mysterious, such as valence (the combining power of an atom in respect to some other such as hydrogen or oxygen), or the remarkable electro-positive and electro-negative character of certain elements, and characteristics which lie intermediate between the two extremes in others, have now been given simple interpretation.

Radioactivity.—As a natural consequence of experiments following the discovery of X-rays by Roentgen in 1895, Becquerel, in 1896, discovered in certain compounds containing the rare heavy element uranium the emission of a very complex radiation that among other properties possesses that of discharging electroscopes and of fogging photographic plates. This phenomenon was called "radioactivity." These two entirely unexpected discoveries, X-rays and radioactivity, are primarily responsible for many of the prodigious advances made in the science of physics in the present century. Without them many other phenomena, such as conductivity of gases and the thermo- and photo-electric effects, might still be without interpretation.

The radiations sent out by radioactive substances were found by years of toilsome investigation to comprise three distinctly different types of rays, which were called first, for want of better names, by the Greek letters Alpha (α), Beta (β), and Gamma (γ). Alpha rays are of corpuscular nature; that is, they are particles, traveling with velocities of a few thousand miles per second. They are easily absorbed; they are positively charged and suffer under a magnetic field a minute, but measurable, deflection which shows their mass to be four times as great as that of the hydrogen atom, or equal to that of an atom of helium. Beta rays, on the other hand, are found to be much more penetrating than Alpha rays, to carry a negative charge, and to possess velocities higher than those of any other known particles. These velocities approach very closely the prodigious velocity of light itself. They suffer strong deflection in magnetic fields, and their mass, except for a slight correction due to their enormous velocity, is found to be

identical with that of the electron. Gamma rays, however, the most penetrating of all radioactive rays, are not of corpuscular nature. They communicate no charge to a plate on which they fall. They are undeflected by electric and magnetic fields, and their velocity within the limits of a rather large experimental error has been found to be the velocity of light itself. It is only within the last few years, indeed, that the Gamma rays, as well as X-rays, have been recognized definitely as radiations of precisely the same nature as light. They are light waves of extremely short wave-length, and, therefore, are properly included in our table of radiations in the preceding section of this chapter. While there are indications that extremely short waves, such as these, may require a modification in some respects of the laws to which light of longer wave-lengths is subject, nevertheless they may be considered in all respects as coming under the general category of light.

In the general phenomena of radioactivity we see the disintegration of an atomic system due to some internal instability, about the nature of which we can at present only speculate. Transmutation of one element into another is here taking place and will be discussed more at length in a later paragraph.

The relation between electricity and radiation.—The connection between electricity and radiation has long been a puzzling question and we do not as yet understand it very well.

When an electrical charge of primitive form, such as an electron, suffers a sudden displacement, there is associated with this displacement a wave of disturbance which travels out through the surrounding space. This is quite analogous to what occurs if one's hand, holding the end of a long rope, makes a sudden sideways motion. Because of the displacement of the hand an impulse is sent along the rope. If several impulses are given in succession, a series of impulses, which we call waves, travel down the rope. If the impulses are rapid, the waves are short; if the impulses are slow, the waves are long.

An old conception, perhaps as good as any, proposed by Faraday, imagines "lines of force" stretching between charges of opposite sign. The corresponding idea in magnetism is illustrated when

filings are sprinkled on a card covering two opposed magnetic poles of opposite sign. The filings arrange themselves along such lines. If there were a free magnetic pole in such a region, it would move along these lines, repelled from one of the two opposed poles and attracted by the other. Precisely similar lines of force may be thought of as existing in the electric field between two electric charges. An isolated charge will have its lines of force extending radially away from it in all directions. If we suppose an isolated negative charge, for example, an electron, is suddenly displaced, the lines of force will also be displaced. This displacement travels out with a finite velocity—the velocity of light. The more sudden the displacement, the steeper is the impulse; the slower the displacement, the more gradual is the disturbance. Extremely slow periodic displacements produce long waves; rapid, high-frequency displacements, relatively short waves. Now, when many atoms are comparatively close together, as in a solid or liquid, their mutual impacts produced by jostling about disturb the electrical systems of which these atoms are composed. This occurs so frequently and in such a haphazard way that impulses of all degrees of suddenness and consequently radiations of all lengths are sent out, and the light, when analyzed, exhibits a continuous spectrum. The natural periods of vibration which these electrical systems in any individual atom possess are completely obscured by the countless millions of impacts which occur. When, however, a substance is in the gaseous condition, with its atoms many hundred times farther apart than they are in the liquid or solid state, disturbances of these electrical systems then become relatively much less frequent. Consequently the jostling is of little importance, and only rarely does a disturbance occur. The radiation emitted now, therefore, possesses only those frequencies that are characteristic of the peculiar structure of the atom involved. Such light, when analyzed, shows its characteristic bright-line spectrum, consisting only of those isolated wave-lengths produced by the frequency of that particular type of atom, the identity of which is thus revealed in the light which it emits.

Hypotheses respecting atomic structure.—In the present state

of our knowledge we know as yet very little, with definiteness, about the structural details of these electrical systems which we call atoms. Only with respect to a few of the simpler types has any progress been made in this direction. We believe that in general the negative electrons are in motion about a nucleus. The mass of the atom for the most part is associated with this nucleus, which is a simple thing only in the case of the lightest atom, hydrogen. This simple hydrogen nucleus comprising, with its attendant planetary electron, the hydrogen atom, is in a certain sense the electron's *alter ego*. It is called by some the "proton" and by others the "positive electron." It is perhaps much smaller even than the electron, maybe only 1/100 of the diameter of the latter. Revolving around it in an orbit at a very great distance compared to its own dimensions, or even the dimensions of an electron, is a single electron.[1] If this tiny system were magnified so that its orbit would be 1,000 times the size of the orbit of the earth around the sun, the electron would be approximately the size of the sun, and the nucleus approximately the size of the earth; and the analogy to a little solar system, therefore, while comparable as to relative magnitudes of the objects involved and the size of their orbits, is a peculiarly topsy-turvy affair with respect to size of its components, because the large, but light, electron revolves about the comparatively small, but heavy, nucleus. On the other hand, quite like the solar system, the bulk of the mass is in the central heavy nucleus. One aspect of this picture is especially noteworthy, and that is that the electron and proton together occupy an entirely negligible portion of the space which, by reason of their motion, one about the other, they fill. That the interior of atoms, even much more complicated ones than hydrogen, is largely empty space is shown by the fact that if either electrons or nuclei are given very high velocities, they will pass right through many thousand atomic systems and create little or no disturbance. Helium nuclei, for example, can be

[1] Atom diameter = electron orbit = 10^{-8} cm., electron diameter = 10^{-13} cm., proton = 10^{-15} (?) cm.

passed through solid glass walls of considerable thickness. They leave no hole because, from what we have seen, the apparently solid glass is largely empty space.

Next to hydrogen in the periodic table lies helium. Helium has a weight of four compared to hydrogen's weight of one. Its nucleus is presumably a complex structure, having a mass of four. It is thought to contain four hydrogen nuclei, or protons. The charge on the helium nucleus, however, is positive only by two units, and consequently we picture as associated with the four protons two nuclear negative electrons which contribute a negligible addition to the mass, but neutralize half of the charge. It may well be that it is this combination of protons and electrons, oppositely charged and in close association, that binds the nucleus together, for the helium nucleus is a very stable affair. This helium nucleus, mass 4, charge $+2$, has been identified as the alpha particle discussed above in connection with radioactivity, and is one of the most stable nuclei known. When it has revolving far outside around it two planetary electrons, it becomes the ordinary neutral atom of helium gas. Two different types of helium atoms are recognized, which differ only in the fact that in one of them the two electrons revolve in concentric orbits, lying in the same plane, but differing in radii, whereas in the other type the electrons revolve in approximately identical orbits, the planes of which, however, are inclined at angles of 120° one to the other. *Such details, even as these simple ones, at present must be considered largely in the nature of working hypotheses only.* The phenomena which these simplest atoms exhibit are so complex that undoubtedly our picture is far from complete.

The next element in the table, lithium, has a still more complicated nucleus, the details of which need not concern us here. Like helium, it possesses two electrons revolving about it in orbits either concentric or inclined. In addition, it possesses a third electron which revolves at much greater distance than the inner two. This atom is the largest of any known; that is, the space occupied by its planetary electron systems is the greatest of any

known system. For, as the planetary electrons become more and more numerous, the scale of the entire structure shrinks considerably, with the result that all atoms are of rather restricted dimensions. Possessing but one electron in its outermost region, lithium resembles our picture of hydrogen in this respect. Lithium is chemically very similar to hydrogen. As we go to more complex elements, we build more and more electrons into outer orbits. Neon, the tenth element, contains two electrons in inner (sometimes called *K*) orbits, and no less than eight in exterior orbits.

The next element beyond neon, sodium, possesses a planetary electron system quite like neon. In addition, there is one more electron whose orbit lies exterior to the ten others in very much the same way that the third electron of lithium lies exterior to the inner two. It is this similarity of structure between lithium and sodium, like that between hydrogen and lithium, all of which possess one external, or "valence," electron outside of a more compact planetary system of nucleus and completely filled inner orbits, that is responsible for the fact that these three elements are similar in chemical behavior. Such relationships may be traced throughout the entire list of elements, and thus do these facts of chemistry find an interpretation.

Ionized atomic systems.—With certain limitations, an atomic system may contain an excess or a deficiency of electrons over the number which its neutral state requires. For example, a helium atom may have one or both of its planetary electrons removed from it; in which case it is of course an ion, singly charged positively if one electron is removed, doubly charged positively if both are removed. In the latter case, it is sometimes referred to as "stripped," since all of its planetary electrons are gone and the nucleus alone remains. This stripped helium atom is the same thing, of course, as the alpha particle mentioned above. A hydrogen atom, obviously, becomes stripped when its lone electron is taken away, what remains being merely the primitive nucleus, the proton. In the interior of stars, alone, are conditions realized in which many of the heavier atoms may be stripped, at least if not

to the nuclei, to the innermost, or *K*, ring of two electrons. The diameters of such stripped atoms may be as much as a hundred times smaller than those of normal atoms, and consequently we must recognize the possibility of densities of matter in the stars which are many thousand times as great as those with which we are familiar in terrestrial substances. One such star has already been mentioned, the companion to the famous "dog star," Sirius.

Transmutation of elements.—In radioactivity we see a property which is associated only with the heaviest, and therefore the most complex atomic systems that we know. We clearly see the transmutation of atomic systems going on. A radioactive change signalizes its appearance by the ejection from an atomic system of either alpha particles (helium nucleii) or electrons or both. These two corpuscular radiations have their origin in the very complex atomic nucleus, which, for some reason as yet unknown, becomes unstable. In the cataclysm which follows there is not only a rearrangement of the nucleus, which usually ejects a certain number of its former members, but subsequently, a reorganization of the complicated planetary system surrounding it. After this has taken place the chemical character of the atom is entirely altered and a real transmutation of matter, from one form to another, has occurred. This change involves a loss of nuclear energy which appears in the high kinetic energy of the ejected alpha particles and electrons. These phenomena first betrayed clearly the enormous amount of energy locked up within atomic systems, energy so great that if its stores could be wisely and in a controlled manner made available for human use, they would presumably supplant all forms of energy such as are now being employed to run the machines of civilization. In radioactivity, however, these transformations are thus far as inviolate from human meddling as are the motions of the stars. Of great significance, however, is the fact that Rutherford has succeeded in effecting the artificial disintegration of many of the lighter elements, indeed all of those whose weights are not multiples of four. In these experiments the disintegration is effected only in one

atom at a time and in those very infrequently, and the energy released is entirely negligible from any useful human point of view. Still more recently there are indications that nitrogen has been disintegrated, the results of the transmutation being hydrogen, helium, and neon. These have been obtained in amounts sufficient for their spectroscopic identification.

The contemplation of what use civilization may make of such stores of energy as may be placed in its hands by the results of the soaring ambitions of these sons of Prometheus should make us pause and consider whether in other fields of human activity we have progressed far enough to be intrusted with such powers. The harnessing of nature's forces for the use of mankind is already producing opportunities for leisure such as are never enjoyed by primitive people. The struggle for existence is greatly lessened by co-operative effort, and almost all classes of human beings find it necessary to devote less and less time to winning the necessities and even some of the luxuries of life. Unless simultaneously with the control of nature's forces we learn to make proper use of our opportunities for leisure time, we may find ourselves in the position of many other civilizations whose perverted activities have resulted in their ultimate decay and total disintegration. Herein lies the warning of modern science and engineering—an imperative summons for us to employ the same qualities of careful organization and analysis of data in the problems of social life that scientific men are using in connection with the less difficult questions of the physical universe. We have learned enough about the nature of the world to realize that perhaps the most important problem that we face is that of the nature of mankind.

SELECTED REFERENCES

1. Sir William Bragg, *Concerning the Nature of Things* (Harper & Bros., 1925).
2. John Mills, *Within the Atom* (D. Van Nostrand Co., 1922).
3. Herbert Dingle, *Modern Astrophysics* (The Macmillan Co., 1922).
4. R. A. Millikan, *The Electron* (University of Chicago Press, 1917).

CHAPTER V

THE NATURE OF CHEMICAL PROCESSES

JULIUS STIEGLITZ

TRANSFORMATIONS OF MATTER

It is a common experience to see matter transformed all about us. In the early spring, our fields are brown, our trees bare, but in the late spring we see them being covered with green. Grass, leaves, crops appear—a wonderful transformation of the lifeless components of the air and soil into living matter of beauty, indispensable to man! And ultimately we see the process reversed and these living things return to dust, air, and water! In every one of us every single moment, millions of such transformations sustain our life and make possible our multifold activities. We take in air, water, and food, which many millions of minute laboratories in us, the body cells, transform in order to supply our needs. They give us heat to keep us warm, energy to work and to think, materials to replace the waste of the living tissues. The infant grows in size and strength to full maturity by transformations of matter.

Further, there is scarcely an article about us which is not the product of some industry dependent on transformations of crude materials taken from many sources. The leather of our shoes is made of hides transformed by tanning. Our linen is bleached. Our clothes are dyed with colors produced from coal tar. Silver and copper coins in our pockets are made from metals obtained from crude ores. Steel is the product of one of the greatest industries.

The science of chemistry.—These few instances illustrate for you the fact that our existence as living men and women, as well as our modern external conditions of life resting on the industries, depend on transformations of matter. The science which tries to explore the nature of the transformation of matter, and which

endeavors to recognize the laws governing these processes, is the science of chemistry. For this reason chemistry has been aptly defined as the fundamental science of the transformation of matter. In the evolution of human thought it emerged as a science only at the very end of the eighteenth century, although it existed in the form of an art from the early days of civilization.

The science of physics.—Physics, the sister-science of chemistry, had an earlier start as an exact science, and concerned itself until recent years primarily with the fundamental problems of the transformation of energy and with the study of the factors which together constitute energy—such as mass and velocity, the factors of kinetic energy. Every transformation of matter is accompanied by energy changes, in the form of heat, electricity, light or other forms, which are set free or are absorbed. Thus, the greatest sources of energy at present used by man are to be found in chemical storehouses such as coal, oil, food, etc. The sciences of chemistry and physics evidently overlap and some of their greatest discoveries have resulted from co-operation between the two. Indeed, in our own day of investigation of the electrical structure of matter itself, physicists and chemists often occupy common ground and in part are working on the same fundamental problems.

It will be inevitable, therefore, that some of the topics already discussed in physics, such as the structure of atoms, will be taken up anew, but the emphasis will be placed now on their relations to chemical processes.

Applications of chemistry and physics.—The illustrations given above, showing how life itself as well as the industries are dependent on transformations of matter, will make clear now why not only the industries but all of the biological sciences are making more and more use of the two fundamental sciences, chemistry and physics, in the effort to solve their great problems. In particular in trying to lift the veil from the amazing riddle of life, biologists are drawing generously on the facts, the laws, the theories, and the methods of investigation of chemistry and physics. Even

psychology, approaching that question of highest human interest, the connection between intelligence and matter, must look to these fundamental sciences for enlightenment on phenomena such as sensitivity, memory, and motor response, which are the basic elements of all human experience. And finally, medicine, charged with the preservation of our health, is studying its problems now with the aid of chemistry and physics in its need of learning how to keep the chemical processes in our body cells working normally. For sickness inevitably follows abnormal processes exactly as a coal or oil furnace with insufficient supplies of air fills the house with deadly carbon monoxide gas and kills where it is intended merely to warm.

It is only right to state frankly that if the answers to the greatest of biological problems still seem remote, it is in large part because chemistry and physics themselves have been advancing too slowly. These sciences have not made available to the biologist all the facts and laws of transformation of matter and energy which are required for the interpretation of his observations. Thus, the unit of life is the cell and yet we have no comprehensive knowledge of the chemical and the physical properties of the constituents of even a single type of cell.

Let us approach our study of the nature of chemical processes therefore with the consciousness that the science of chemistry is in a state of evolution, growing from day to day, and that the most we can expect to realize now is an outline of thought as it exists today in some of our minds.

Chemistry an experimental science.—Let us also understand that chemistry is an experimental science, evolving its thought and testing its conclusions with the aid of experimental work. You will find too that in co-ordinating the facts and teachings of experiment, chemistry is compelled to draw on our powers of imagination, controlled by the critical questioning of our intelligence, for chemistry has found the most satisfying interpretations of the visible, gross observations of our senses in conceptions involving rapidly moving material particles which are far too mi-

nute to be individually seen, weighed, or counted. It is because the whole thought of chemistry is evolved from the application of intelligence and imagination to experimental results, that we shall develop in these lectures our own study of the nature of chemical processes with the aid of experiments which should bring home to you the basis and the nature of chemical reasoning.

Non-chemical transformations.—Now let us try to recognize first what a chemical process is: If we split kindling, the wood remains wood—it is simply broken up mechanically. Brass turnings, taken from a brass bar, still are brass in a finer state of division. If we mix, with great care, powdered charcoal, sulphur and niter, we have gunpowder; but the ingredients are still all there: a magnifying glass will show black carbon, yellow sulphur, white niter reposing side by side and we can extract the niter with water, the sulphur with a proper solvent (carbon disulphide) and leave the carbon; after evaporation of the two solutions, we can show you the three ingredients (*Exp.*). Gunpowder is simply a mechanical mixture of the ingredients—ready, it is true, for a tremendous chemical change.

Mix sugar and water: the sugar dissolves, changes its physical state, but it can be recovered unchanged in weight and properties if we allow the water to evaporate. We should not call this a chemical process, but rather a physical one, a change of state.

These instances represent mechanical or physical processes, not chemical; the inherent matter of the components has not been changed: only their distribution, their location, has been affected.

CHEMICAL PROCESSES

Chemical transformation by combination.—In contrast, let us observe some processes which do transform matter and are chemical. Iron rusts in the air, the bright metal turns into a red, friable mass. We can hasten the process with the aid of heat (*Exp.*). When we examine rust, the strongest microscope shows only red particles, no metal; when we melt it at very high temperatures, it cannot be poured to form iron rods. The iron is trans-

formed completely into a new product, rust. What has brought about this deep-seated change? For many years it was believed that in rusting, iron allowed an ingredient of the metal to escape. A great French chemist, Lavoisier, at the end of the eighteenth century opened the way to a true understanding of this and many other fundamental chemical processes by studying such processes with the aid of the balance. One of the very first lessons the balance taught (1772–77) was that when a substance like iron or coal is burned, the product formed is heavier than the original iron or coal (*Exp.*).

EXP.: A large magnet holding iron filings is attached to the hook above the pan of a suitable balance and balanced by weights on the second pan. The filings are heated with the aid of a flame and as they are oxidized, the side of the balance holding the magnet and the iron sinks.

In the combustion, something ponderable, some material must be captured from the surrounding atmosphere. Lavoisier easily recognized the oxygen of the air as the vital component necessary for combustion. Indeed, if we use pure oxygen (*Exp.*) we see that iron burns with a white dazzling light, because the process is so rapid and powerful. The change of iron into rust, as the balance shows, evidently is the result of a combination of two materials, iron and oxygen, into one new material. Combination represents the first of the fundamental types of chemical processes which we shall consider.

By the introduction of an instrument of precision, the balance, for the study of chemical processes, Lavoisier laid the foundation on which chemistry has grown to be an exact science. All chemical processes are now studied with the aid of instruments of precision and the results are expressed precisely in numbers—with the consequence that many important new results can be predicted as possible under definite conditions, and impossible under other conditions, much as the astronomers predict the appearance of comets years ahead.

Chemical transformation by separation.—It is not easy to resolve rust directly into its components, but it has been done

with the aid of an electric current and the iron and oxygen have been recovered. It is more convenient to illustrate the chemical process of separation with another red powder, mercuric oxide. When heated, this breaks down into liquid metal droplets of mercury, and into a gas, which we recognize as oxygen by its great power to support combustion (*Exp.*).

The electric current is a second powerful means of effecting chemical separation. One illustration must suffice: an electric current passed through water (*Exp.*) produces two gases—one we recognize as oxygen (it lights a glowing splinter); the other gas does not support combustion, but is itself inflammable. It has been happily named hydrogen because it comes out of water and again forms water when it burns in the air and combines with oxygen (*Exp.*).

Chemical transformation by exchange.—There is still a third fundamental chemical process besides combination and separation—one involving both of these simultaneously. Barter and exchange early appealed to mankind and made civilization possible. And similarly in chemistry, one of the most common of all processes is transformation by exchange. Thus, while it is difficult to separate iron and oxygen outright and recover them from rust, we can very readily get back the iron which we want by giving the oxygen carbon in exchange. At a red heat we find that iron oxide and carbon form iron and carbon oxide. That is part of the process underlying the great steel industry, as no doubt you all know. In this process you will note we have both separation (the oxygen from iron) and combination (carbon and oxygen).

We may illustrate this type of action with the aid of an unusually active metal, sodium, extracted from common salt. If we drop a piece of sodium into water, we notice a violent evolution of a gas, which we recognize as hydrogen by collecting it and lighting it. The water has exchanged part of its hydrogen for sodium, forming a solution of caustic soda (*Exp.*).

It will be sufficient for our purposes to summarize what we have learned thus far by saying that chemical processes are

primarily of three types: processes of combination, or synthesis; processes of separation, or analysis; processes of exchange, involving both of these.

Chemical elements.—Now, by using all of the known methods of analysis, chemists found that whereas hundreds of thousands of substances could be resolved into simpler components, there were a few materials which withstood all processes of separation and came out intact. These comparatively few substances, some ninety odd, were called elements. Heat and electricity and the most ingenious efforts of separation by exchange—all failed with these substances. Some of the most important elements, or simples, are metals, such as iron, zinc, lead, copper, silver, gold, platinum, sodium, etc.; others are non-metallic elements, including such well-known substances as carbon, oxygen, nitrogen, hydrogen, chlorine, iodine, sulphur, phosphorus, etc.

Work of the most recent years, as Professor Lemon has shown you, has taught us that these elements are really extraordinarily stable combinations of only two elementary forms of matter—both electrical in character, the one consisting of electrically positive protons, the other, of negative electrons. This epoch-making discovery of our generation was not at all surprising, but was in a way anticipated by almost a hundred years by Prout, an English physician who suggested that hydrogen is the one basic element from which all other elements are formed. It always was a severe tax on the imagination to accept some eighty to ninety elements—but experimental proof of the composite character of the elements was not forthcoming until toward the very end of the last century. For the present, let me only say that one element, radium, was first observed to decompose spontaneously: that gave the world of chemists and physicists the needed clue.

We shall delve more deeply into this fascinating and important chapter of modern chemistry and physics after we have gone further in comprehending some of the most important discoveries of chemistry concerning the so-called elements, which still are true. We shall use the term element in its current sense for the

ninety odd substances which, after they have been extracted out of the hundreds of thousands of products offered us by Mother Earth, have resisted all the ordinary methods for the separation of substances into components.

Compounds.—In contrast to the elementary substances, a compound is produced by the combination of two or more elements. Thus, iron rust is a compound of iron and oxygen; it has its own characteristic properties and is neither iron nor oxygen, but a new substance, iron oxide; water is a compound of hydrogen and oxygen; sugar is a compound of three elements—carbon, hydrogen, and oxygen.

Our whole universe consists, then, chemically speaking, of two kinds of matter—elements and compounds. There are hundreds of thousands of compounds already known. They, with the elements, form our stars and build up our earth, geologically speaking; they build up all living matter, plant and animal, and all products of industry. Mixtures of compounds are the rule: our rocks are, with few exceptions, mixtures, as can often be seen by the naked eye. Minerals, like quartz, frequently are fairly pure compounds; the ocean with its salts dissolved in water is a mixture, but carefully distilled water is pure. All living matter contains an indescribably complex mixture of thousands of compounds.

That is the world as it appears before the eyes of a chemist. You can readily appreciate that one of the undertakings occupying the time of thousands of chemists has been the task of separating and identifying the untold number of different compounds existing in the inorganic and organic world of today—exactly as many botanists and zoölogists devote their lives to the studying and classifying of thousands of species of plants and animals.

SOME PRINCIPLES OF CHEMISTRY

With the aid of this wealth of material, the leaders in chemistry have recognized many laws and principles of chemical action. We shall try to develop a few of the most important principles in order that you may take with you something of the mode of

reasoning which has made chemistry the powerful instrument it is today.

The atomic theory.—If we examine the rust produced by the combination of iron and oxygen even with the most powerful microscope, every finest particle is found to be the red oxide which contains both iron and oxygen. How far can this division go? The Greeks developed the philosophic concept of atoms—but chemists discovered the scientific atom, that is, the actual atom. This discovery was one of the first great consequences following Lavoisier's introduction of the balance as an instrument of precision in the study of chemical processes. We find, first, that every pure compound has a definite composition by weight: for instance, pure water always has 2 parts by weight of hydrogen combined with 16 parts by weight of oxygen. Why such a definite, exact ratio? Further, we often find the same elements forming not only one compound, but two or more compounds with one another. Thus, hydrogen peroxide, like water, consists of only hydrogen and oxygen—but only 1 part by weight of hydrogen is combined with 16 parts of oxygen, or 2 parts with 32 parts of oxygen. Note that we have exactly twice the weight of oxygen combined with a definite quantity of hydrogen in hydrogen peroxide that we have in water.

Carbon and hydrogen form many compounds with each other. The simplest have this composition:

	Parts by Weight	
	Hydrogen	Carbon
Marsh gas...........	$4=4\times 1$	12
Olefiant gas..........	$2=2\times 1$	12
Acetylene............	$1=1\times 1$	12

Each individual compound evidently has a definite composition, and there is clearly a very simple relation among the three compounds mentioned: The same weight of carbon is combined with whole multiples of a given weight of hydrogen.

Carbon and oxygen form two common oxides—the deadly monoxide of the garage and the pleasant dioxide of the soda fountain. The monoxide contains 12 parts by weight of carbon com-

bined with 16 of oxygen; the dioxide contains 12 parts by weight of carbon and 32 (2×16) of oxygen.

We have the ever recurrent characteristic number 12 for the combining weight of carbon and 16 for that of oxygen, as shown in these oxides of carbon as well as in the oxides of hydrogen; and we have 1 for hydrogen.

The great English chemist, John Dalton, of Manchester, found the key to facts like these and gave the world the atomic theory (1803–8). In its simplest form, the theory is:

1. Each element consists of ultimate particles called atoms. Atoms were considered indivisible, but we know now that they consist in fact of protons and electrons. They are, however, with few exceptions, extraordinarily stable.

2. The atoms of a given element show the same chemical behavior and they were all supposed to have the same weight. Modern atomistics, we shall find, has also revised this conclusion in certain particulars, especially in regard to the weights of the atoms. (See "isotopes," p. 147).

3. Chemical combination takes place by the union of one or more atoms of a given element with one or more atoms of another element or of other elements.

Convenient symbols were devised to designate the various elements, such as H for hydrogen, C for carbon, O for oxygen. Each symbol represents an atom of the element with its characteristic relative atomic weight. We have not the time to tell you just how the atomic weights have been determined; it must suffice to say that arbitrarily we have given the oxygen atom the weight 16 ($O = 16$) and that we express the atomic weights of all the other elements with reference to that standard. Thus:

	Element			
	Hydrogen	Carbon	Oxygen	Iron
Symbol....................	H	C	O	Fe
Atomic Weight............	1	12	16	56

The actual weight of a single atom of hydrogen is now known to be 1.66×10^{-24} or $1.66/10^{24}$ gram.

Compounds are formed by the union of atoms of different elements. The smallest particles of any substance, element or compound, existing in a free state are called molecules. We have definite and exact methods for determining the weights and composition of molecules and we use the results of such determinations for expressing conveniently the composition of molecules with the aid of the atomic symbols. Thus we have such well-known formulas as:

H_2, hydrogen	H_2O_2, hydrogen peroxide	H_2C_2, acetylene
O_2, oxygen	H_4C marsh gas	CO, carbon monoxide
H_2O, water	H_4C_2, olefiant gas	CO_2, carbon dioxide

Since a pure substance, such as carefully distilled water, represents simply an aggregation of its own molecules, it is evident that the composition of the pure substance gives us also the composition of the molecule. In a drop of water (0.05 cc.) there are about 2×10^{21} molecules of water. What this number means has been aptly brought nearer to our understanding by this illustration: There are said to be nearly 2,000,000,000 people on the face of the globe and if each one of these were to count 3 molecules of water per second, it would take all of the inhabitants of the earth something over 10,000 years to count the molecules in a single drop of water.

Mixtures are aggregates of molecules of different compounds: thus, air consists chiefly of molecules of nitrogen (about 79 per cent) and of oxygen (almost 21 per cent) with a very small proportion of molecules of water, carbon dioxide, and very rare gases.

Some fundamental questions.—These considerations bring a series of questions to our minds: (1) What forces hold the atoms together in a molecule? (2) Why do atoms of certain elements combine, sometimes with great violence—while others are inert toward one another? (3) How are the atoms arranged in the molecule?

Forces holding atoms in chemical combination.—We cannot answer all of these questions at once, although they should interest us tremendously, as our very life is wrapped up in them. First,

what is the nature of the forces holding the atoms in the molecule? What forces hold together the three atoms of the molecule of water, the thirty atoms of the molecule of indigo, the thousands of atoms in a molecule of protein? We shall find that this question is intimately connected with the second question—why certain elements have a great tendency to combine with one another, which we are wont to call exhibiting a great affinity for one another, whereas other elements are indifferent toward one another.

Neither of these fundamental questions could be answered thirty years ago. Both will find their answer, we now believe, in the modern discovery of the electrical structure of the atoms of which all matter is built up. The application of the laws of gravity to stellar systems years ago gave to man an understanding of the movements of heavenly bodies, and the insight thus gained of the orderliness of our universe constitutes one of the greatest inspirational experiences of the human race. Today we stand at the threshold of another profound experience in the meaning of things—this time at the other extreme of dimensions. Atoms are constellations so small that myriads of them are gathered into a single particle of dust; yet the recognition of their electrical character is making possible the application to them of the laws governing electrical forces—for instance, the law that oppositely charged particles attract each other and particles with like charges repel each other. Since the atoms are the units on which the chemical processes of life ~~and industry~~ depend, a study of the atoms from the point of view of their electrical structure should give us some insight into the laws and forces underlying all such processes. Our knowledge is as yet fragmentary, for the discovery of the electrical structure of matter is recent; but so much has already been found out that for the first time in history an experimental study of the ultimate causes of chemical action is possible. The most impressive result of these studies is to be found in the revelation of harmonies and orderliness prevailing in the world of the infinitely small exactly as in the vast worlds of the infinitely great.

Structure of atoms.—Let us turn then to the consideration of

the structure of atoms from the point of view of chemistry. Professor Lemon has already outlined to you the modern theory of the structure of atoms, with emphasis on its physical features—we shall consider those phases of it which contribute to the understanding of chemical processes.

As you have learned, there are, according to our present knowledge, only two actual elementary kinds of matter. The first one of these to be discovered and identified is associated with negative electricity and consists of discrete particles called electrons, or particles of negative electricity. Contemporaneous workers at the end of the last century obtained clues to this new fundamental form of matter, but pre-eminent was the work of J. J. Thomson, the great English physicist, who in 1897 discovered that the electrons (he called them corpuscles then) exist in the atoms of all of the so-called chemical "elements." Thomson also determined that these particles carry a negative electrical charge, and have a mass only of about 1/1845 the mass of the lightest atom, the hydrogen atom.

The other ultimate form of matter also consists of atoms of electricity, but positive in character. They are called protons, and were first recognized in 1911 by Rutherford, another great English chemist and physicist. The proton is much heavier than the electron, containing all of the mass of the hydrogen atom except the minute mass of the electron, but the proton occupies an exceedingly small volume. Its charge is equal to that of the electron, but opposite in sign. When an equal number of protons and electrons exist together, we discover no free charge.

The atoms of all chemical elements are built up of protons and electrons. Every uncombined atom is electrically neutral and must, therefore, contain the same number of protons and electrons. Hydrogen has atomic weight 1 and practically all of its mass is that of its proton; since the atomic weight of any element is expressed in the same units, it follows that the atomic weight of an element equals, numerically, the number of protons (and also the number of electrons) in its atom. These atomic aggrega-

tions of protons and electrons range from the simplest, the hydrogen atom, with but one proton and one electron, to the most complex known, that of uranium which contains 238 protons and 238 electrons.

It is assumed that in the hydrogen atom the massive but minute proton is in the center of the atom and attracts the electron which probably revolves around it.

Nucleus of an atom; kernel of an atom; valence electrons.—Each atom of the other elements is considered to contain a nucleus built up of protons and electrons, and this nucleus represents the chief mass of the atom. The exact character of the forces holding protons and electrons in nuclei is not known. We do know that the nuclei of the atoms of all but a few elements are extraordinarily stable. The only common exceptions to this are found in the atoms of certain rare elements of very high atomic weight like radium and thorium, whose nuclei decompose spontaneously. Nuclear stability makes possible the existence of the chemical elements.

Now, all of the protons of an atom are in its nucleus, but only a part of its electrons are located there; for the elements whose atoms have low atomic weights, only half of the electrons are usually in the nucleus. The remaining electrons seem to be distributed in so-called "spheres," or "shells," around the nucleus at relatively great distances. Of greatest importance for chemical processes are the electrons in the outermost sphere, which we distinguish as "valence electrons." It is these valence electrons which make chemical combination and processes possible, as we shall presently see. The nucleus with the outer electrons other than the valence electrons is called the kernel of an atom.

J. J. Thomson, in his earliest papers following his discovery of the electron, called attention to the fact that atoms composed of positive and negative electricity should show varying degrees of stability according to the number and distribution of the charges. Some systems should be so stable that they should tend neither to gain nor to lose electrons and should thus remain electrically

neutral and chemically inactive. Other atoms might very well go over into new, more or less stable, electrical systems by losing or by gaining electrons, and thereby acquire excess positive or negative charges. The development of such excess charges should make possible chemical combination. This forecast by the great founder of the present knowledge of the structure of atoms and of its relation to chemical activity, has been fully confirmed in substance, but developed and modified in detail by discoveries of later workers.

Types of atoms: helium type.—We are now prepared to consider from the point of view of present theory different types of atoms, with special reference to their chemical activity.

Helium is an element whose atoms represent especially stable electrical aggregations. The atomic weight of helium is 4, and its nucleus therefore contains 4 protons. Additional information on the composition of the nuclei of atoms is obtained from the atomic numbers of elements. It must suffice to say now only that the atomic number represents the excess of protons over electrons in the nucleus of the atoms of an element. That is the same as the net positive charge on the nucleus. Evidently, it also is the same as the number of electrons in an atom outside of its nucleus. It may be determined from the X-ray spectrum of an element. The atomic number of helium is 2, the excess positive charge on the nucleus is therefore 2, and its nucleus consists of 4 protons and 2 electrons. Figure 20 (*a*) gives us one of the diagrammatic pictures proposed for the nucleus.

We represent this helium with the excess of two positive charges by the symbol He^{++}. It is this kind of helium, He^{++}, which is ejected in the form of alpha rays from atomic nuclei of unstable, radioactive elements like radium. Each particle of the alpha rays, however, captures two electrons from surrounding atoms and forms electrically neutral helium. The two electrons are supposed to move in orbits relatively far away from the nucleus, but are held so firmly that helium represents an atom of the highest degree of stability (see Fig. 20 [*b*]). Under ordinary con-

ditions it shows no tendency to become positive by the loss of either one or both of these electrons. Nor does a helium atom seem to have the power to capture and hold an additional electron and form an electro-negative atom, He^-. Of particular significance for chemistry is the fact that with this electrical stability, helium, as far as we now know, is chemically inactive.

Of the same type of electrical stability and chemical inertness is the element neon, whose atomic structure is also most instructive. Neon has the atomic weight 20 and the atomic number 10 with a nucleus of 20 protons and 10 electrons. Two more electrons are firmly held by the nucleus, as in the case of helium and of all other atoms (except hydrogen). That leaves an outside shell of 8 electrons, and it is an impressive fact that this shell of 8 electrons, an octet, represents another extraordinarily stable system, which tends neither to add to its number nor to lose any electron. And again, with this inability to acquire a stable excess positive or negative charge on its atoms, neon, like helium, is chemically inert (see Fig. 20 [*c*]).

Metal type.—Of quite a different chemical type are elements of a second group, such as hydrogen, and sodium, iron, zinc, and other metals. The hydrogen atom consists of one proton and one electron, but it is rather easily deprived of its electron and forms H^+, a hydrogen ion,[1] as we have it in water and in acids. We shall presently see that the activity of hydrogen, for instance, its tendency to combine explosively with oxygen to form water, seems to be intimately associated with this atomic property. The metal sodium, of atomic weight 23 and atomic number 11, has in its atom a nucleus of 23 protons and 12 electrons, a shell of 2 electrons and a further shell of 8 electrons, as in neon. Beyond this shell, there is a valence electron which is very loosely held (see Fig. 20 [*e*]). This electron escapes so easily to atoms with a greater

[1] The origin of the name ion is given on p. 140. The term is used now to designate any atom, or group of atoms, which has an excess positive charge (a cation), or an excess negative charge (an anion). K^+, Na^+, Ca^{++}, Al^{+++} are common, positively charged ions; Cl^-, NO_3^-, $SO_4^=$ are common instances of negatively charged ions.

attraction for electrons that sodium is an exceedingly active metal, as we found in its violent reaction with water. We may now formulate this action as consisting primarily in the formation of sodium ions and hydrogen by the escape of electrons from sodium atoms to hydrogen ions of water (see p. 139). The reaction may be expressed concisely in the form of a chemical equation:[1]

$$2Na + 2H^+ \rightarrow 2Na^+ + H_2.$$

Let us note that the sodium ion, Na^+, left by the escape of the valence electron, has now an outside shell of 8 electrons, as in neon; and this complete shell of 8 electrons like the one in neon (see Fig. 20 [*c*] and [*e*]) does not show any tendency to lose any of its electrons and develop a greater positive charge. But in this instance we have already one excess positive charge on the kernel, through the escape of the valence electron. We find sodium ions, Na^+, capable of combining chemically with negatively charged atoms, such as chloride ions, Cl^-, oxide ions, $O^{=}$, hydroxide ions, ^-OH, etc.

Atoms of metals, in general, may be deprived of one or more valence electrons and thus become positive ions. The ease with which the valence electrons are lost is very great in the case of some metals, very small for others. In the baser metals, such as zinc and iron, the tendency is very great indeed: $Zn \rightarrow Zn^{++} + 2e$ and $Fe \rightarrow Fe^{+++} + 3e$. That is why zinc and iron corrode easily in air and why zinc is a favorite component of electrical batteries. Their valence electrons escape to oxygen atoms in the air, forming oxide ions, $O^{=}$; the oxides $Zn^{++}O^{=}$ and $Fe^{+++}{}_2O^{=}{}_3$ result. In one type of battery (*Exp.*) the valence electrons coming from myriads of zinc atoms in the zinc rod flow through the wire, producing a current of electricity; they are absorbed by cupric ions of the blue vitriol surrounding the other electrode. Zinc ions,

[1] In a chemical equation the sign $\rightarrow$ means "forms" or "produces." We recall that the symbols designate atoms of elements, each with its characteristic weight. The foregoing equation states, therefore, in addition to what is expressed in the text, that 46 parts by weight of sodium react with 2 parts by weight of hydrogen-ion and produce 46 parts by weight of sodium-ion and 2 parts by weight of hydrogen

Zn^{++}, go into solution, and copper, Cu, is deposited: $Zn + Cu^{++} \rightarrow Zn^{++} + Cu$.

The atoms of the noble metals, such as silver, gold, and platinum, show a very great resistance to the loss of their valence electrons; that is, the neutral electrical systems, Ag, Au, Pt, are far more stable than Ag^{+}, Au^{+++} or Pt^{++++}. In fact, one need only get a little silver nitrate ("lunar caustic") on one's fingers and note the deep black stain formed, to realize how readily Ag^{+} particles capture electrons from atoms in our skin, depositing black silver and incidentally destroying components of the skin. Even copper is formed easily from Cu^{++}, as the above experiment showed.

Oxygen type.—In a third great group of elements, the atoms become more stable by capturing electrons. Oxygen is typical of such elements: since its atomic weight is 16 and its atomic number 8, its nucleus contains 16 protons and 8 electrons; there are the usual 2 electrons outside of the nucleus. That leaves us only 6 electrons for the valence shell. This is 2 electrons short of a stable octet. We need only observe the avidity with which oxygen burns iron or coal or explodes with hydrogen, to realize the tremendous power with which its atom captures 2 electrons and thereby forms stable $O^{=}$.

Nitrogen type.—There is a last group of elements of particular interest to us, whose atoms represent electrical aggregations which can either capture electrons and complete their valence shells of 8, becoming negatively charged, or they can also lose their valence electrons and become positively charged. These are of especial interest to us because carbon and nitrogen belong to this class and they are, with hydrogen and oxygen, the two most important elements in organic compounds which are of great moment to us as living beings. Thus, the nitrogen atom, with an atomic weight of 14 and an atomic number of 7, after the nucleus and the usual 2 electrons held nearest to the nucleus are provided for, has 5 valence electrons. Nitrogen forms two series of especially important chemical compounds. In ammonia $N^{\equiv}H^{+}_{3}$, the nitrogen atom has

its full complement of 8 electrons[1] and has the power to hold $3H^+$. On the other hand, in nitrates such as saltpeter, $K^{+}\,{}^{-}O^{-}\,{}^{+}N^{\ddagger\ddagger}_{++}{}^{=}O_2$, nitrogen has lost all of its electrons and is bound to negative oxygen.[2] The nitrogen in gunpowder, in nitroglycerine, guncotton, and T.N.T., is of this type, and it is apparently the ability of the nitrogen atoms to rob neighboring carbon atoms of their electrons that gives to these well-known explosives their tremendous power.

STRUCTURE OF ATOMS AND CHEMICAL PROCESSES

With this survey of the structures of four different types of atoms, we are prepared to begin to understand the nature of chemical processes from a more fundamental point of view than ever before. Let us consider the burning of hydrogen (or of iron) in oxygen. Hydrogen (iron) atoms become more stable by losing valence electrons, oxygen atoms are avid to complete their octets. The inevitable happens when by heat initial resisting forces,[3] inhibitions, as it were, are removed, and the electrons escape from hydrogen (or iron) to oxygen with a great release of energy:

$$\begin{array}{ll} 2H_2 - 4e \rightarrow 4H^+ & 4Fe - 12e \rightarrow 4Fe^{+++} \\ O_2 + 4e \rightarrow 2O^{=} & 3O_2 + 12e \rightarrow 6O^{=} \\ \hline 2H_2 + O_2 \rightarrow 2H_2^{+}O^{=} & 4Fe + 3O_2 \rightarrow 2Fe_2^{+++}O_3^{=} \end{array}$$

We can readily demonstrate the electrical character of the forces driving elements into chemical union as well as of the forces breaking down chemical combinations. In the first place, we shall bring iron and oxygen together in such a way that the iron cannot transmit its electrons to oxygen by contact, but that it will be in a position to do so by sending the electrons through wires. We

[1] Later on the question of the supposed distribution of the electrons will be considered in connection with the theory of the electron doublet valence forces (see p. 138).

[2] *Ibid.*

[3] The resisting forces are perhaps due to the difficulty of the first breaking down of molecular hydrogen H_2 and molecular O_2 into free atoms, H and O. It is the free atoms which easily lose or gain electrons, respectively, and which are chemically active.

have here an instance of what is called chemical action at a distance. An iron plate dips into a salt solution and oxygen gas passes through a so-called gas electrode[1] where it comes into contact with platinum gauze coated with finely divided platinum black, and passes in bubbles into a salt solution; the iron and the platinum wire of the gas electrode are connected with a sensitive voltmeter or chemometer,[2] and the circuit is closed by means of a salt-bridge connecting the salt solutions (see Fig. 21).

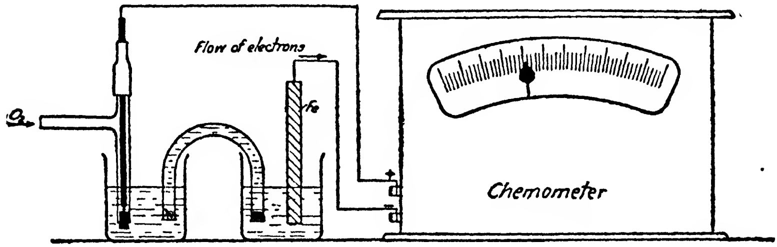


FIG. 21.—Experiment to demonstrate the electrical character of oxidation.

Now, if the chemical activity of iron toward oxygen really originates in the power of the iron atom to give up valence electrons and of the oxygen atoms to capture these electrons in order to complete their valence octets, then a current of electrons should flow from the iron plate through the chemometer to the oxygen. We see that is clearly the case. Closer examination would show that in this process Fe finally becomes Fe^{+++} and O becomes $O^{=}$, exactly as in the direct union of the elements.

A similar current is obtained if we use two gas electrodes, one for hydrogen gas, the other for oxygen (*Exp.*).

Thus, we find the process of oxidation—which sustains our life, runs our furnaces and our industries, and which is a typical process of chemical combination—is fundamentally electrical in character and finds its origin and its expression in the electrical properties of atoms.

Structure of atoms and decomposition.—Separation, or analy-

[1] Cf. Stieglitz, *Qualitative Analysis* (The Century Co., 1911), I, 281.

[2] Cf. *Ibid.*, p. 253.

sis, is the reverse of combination, and it is easy to understand why a sufficiently powerful electrical current decomposes water (p. 122); electrons are fed to positive hydrogen ions at the negative electrode and taken from negative oxygen ions at the positive electrode:

At the negative electrode: $4H^{+}+4e \rightarrow 4H \rightarrow 2H_2$
At the positive electrode: $2O^{=}-4e \rightarrow 2O \rightarrow O_2$

Structure of atoms and action by exchange.—Chemical action by exchange is readily understood, too. For instance, for the action of decomposition of water by sodium, we have (p. 138):

$$2Na+2H^{+}\,{}^{-}O^{-}\,{}^{+}H \rightarrow H_2+2Na^{+}\,{}^{-}O^{-}\,{}^{+}H \;.$$

Union of atoms by electrical forces.—We note that in the compounds, water, sodium hydroxide, and iron oxide, the forces holding the elements in chemical union are considered to be the attractive forces between positively and negatively charged particles. "Atoms cling to their charges and oppositely charged atoms cling to each other" was, in 1881, Helmholtz's apt summary of the nature of chemical combination. The power of these forces is indicated by the calculation by Helmholtz that the electrical force holding two positive hydrogen atoms in combination with a negative oxygen atom in a molecule of water would be 71,000 billion times as great as the gravitational attraction between the atoms.

Two types of electrical union of atoms.—This kind of chemical union of atoms by virtue of the electrical forces of attraction between oppositely charged atoms represents the simplest type of combination. We may call it the "dualistic" or "ionic" type of union—two differently charged ions taking part in the union. In recent years a second type of union, also based on electrical forces, has been recognized, especially under the leadership of Professor G. N. Lewis, of the University of California. This second kind of combining force seems to be even more powerful, and to lead to more stable combinations, than the type first discussed. There is evidence that the two types often merge into each other.

Electron doublet type.—The Danish physicist Bohr proposed for the force holding two atoms of hydrogen in a molecule H_2 a pair of electrons revolving in orbits between two protons:[1] ⊕ : ⊕ . The attraction of the negative charges of the electron pair is thus exerted on the two protons, forming a molecule. Langmuir has recently shown that when two atoms of hydrogen combine to form molecules H_2 of this type, an enormous amount of heat is evolved and higher temperatures are produced than in the burning of hydrogen and oxygen. The discovery has been applied industrially (atomic hydrogen torch). This great heat evolution of the action $2H^+ \cdot \rightarrow H^+ : H^+$ is evidence of the tremendous power of the electron doublet in the union of atoms. According to Bohr, Lewis, and others, the atoms in the compounds of many elements may in this way share pairs of valence electrons, which hold the positive kernels in chemical union. Thus, for marsh gas and for ammonia, we would have the structures:

```
            H+                           H+
            ··                           ··
            +                            +
    H+ :+C+: H+          and      H+ :+N‡:
            +                            +
            ··                           ··
            H+                           H+
```

The union of atoms by electron doublets makes it possible for atoms, by sharing electrons, to complete their octets mutually and thus to attain the condition of saturation and stability associated with octets. Thus, while a carbon atom has only 4 valence electrons in it and an oxygen atom only 6, in their combination to form carbon dioxide CO_2, we see the 16 electrons so distributed that each atom is surrounded by an octet of valence electrons:

```
 ⁝O⁝ C ⁝O:
 6+ 4+ 6+
```

Polarity.—However, the electron pairs may be drawn closer sometimes to the one, sometimes to the other, atom. In the mole-

[1] An electron is often indicated, as here, by a dot · .

cules of very many compounds the pair appears to remain definitely much closer to the kernel of the one atom than to that of the other atom, as a result of the net sum of all electrical forces. Thus, for carbon dioxide, we are supposed to have:[1]

$$\begin{matrix} \vdots\mathrm{O}\vdots & \mathrm{C} & \vdots\mathrm{O}\vdots \\ 6+ & 4+ & 6+ \end{matrix}$$

The positive charges on the kernels of the atoms are given under the symbols. The position of the electrons close to the oxygen atoms is intended to indicate that their orbits are closer to the oxygen atoms than to the carbon atom. As a result the oxygen atoms, each with 8 negative electrons and a kernel charge of 6+, are relatively negative and have the power to attract and hold positive atoms (e.g., Na^+, K^+, etc.); the relatively positive carbon atom can attract and hold negative atoms or groups (e.g., ^-OH). In this way carbon dioxide combines chemically with sodium hydroxide $Na^{+-}OH$ to form sodium bicarbonate (NaO) (HO) CO (baking soda)—a typical illustration of growth of molecules through the electrical forces exerted by their atoms. This view of the structure of carbon dioxide may be expressed more simply in the formula

$$\mathrm{O}\overset{-}{\underset{-}{}}\ \overset{+}{\underset{+}{}}\mathrm{C}\overset{+}{\underset{+}{}}\ \overset{-}{\underset{-}{}}\mathrm{O}\ .$$

To distinguish polarity of this type in "doublet" union from the polarity of compounds of the ionic type, we will indicate in future the charges on the latter in heavy type, **+** and **—**, and on the former in light type, + and –. The – sign then represents a doublet of electrons. Thus, we have: $Fe_2^{+++}\ O_3^{=}$ and $\mathrm{O}\overset{-}{\underset{-}{}}\ \overset{+}{\underset{+}{}}\mathrm{C}\overset{+}{\underset{+}{}}\ \overset{-}{\underset{-}{}}\mathrm{O}$. A – charge is always equivalent to a doublet : that is, ^-X and $:X$ are equivalent.

In such combinations as those of carbon atoms with other carbon atoms, as are met with in the compounds of organic chemistry, the degree of relative polarity no doubt is greatly re-

[1] The arrangement in space (tetrahedral) of the doublet pairs will be discussed later (p. 153)

duced. In extreme cases like that of ethane, C_2H_6, there is probably no polarity between the two carbon atoms and only slight polarity between the carbon and hydrogen atoms:

$$(\mathrm{H}^+ \;:)_3 \overset{+}{\underset{+}{+}}\mathrm{C}+ \;:\; +\mathrm{C}\overset{+}{\underset{+}{+}}(:\; {}^+\mathrm{H})_3 \;.$$

Stability of the electron doublet type of union.—This type of union is presumed to be the source of the striking stability of many thousands of organic and inorganic compounds.

Let us repeat that we shall distinguish the two types of electrical union between atoms as the "ionic" type (as we have it in ferric oxide, $Fe_2^{+++}O_3^{=}$) and the "doublet" type of union which may be either polar, as in carbon dioxide (see above), or non-polar as in marsh gas (see p. 138).

Electrolytes and ionization.—These differences in the kinds of union between atoms in molecules are of decisive importance in distinguishing two fundamental types of chemical compounds. Molecules of the "ionic" kind are found to break down very easily into their electrically charged components when they are dissolved in such a solvent as water. Thus, sodium chloride, on solution in water, separates into positive sodium ions and negative chlorine ions: $Na^{+-}Cl \rightleftarrows Na^{+} + Cl^{-}$.

The separated electrified particles move under the impulse of an electrical potential, say of a battery; the positive ions (Na^+) are attracted by, and move to the negative electrode, the negative ions (Cl^-) go to the positive electrode. They thus carry the electrical current from electrode to electrode through the solution (*Exp.*). Because they move, the particles were called ions (the migrating particles) by Faraday.

Chemical activity of electrolytes.—Compounds whose molecules contain atoms held in ionic union thus form electrolytes. Because of their ionization, such compounds acquire an extraordinary speed in chemical action; this is no doubt due to the fact that ions are free to react at once and need not first overcome initial resisting forces (see p. 135). The following illustrations will

make this fact clear. Of such electrolytes, those which form hydrogen ions, H^+, are distinguished as acids. Hydrochloric acid ionizes as follows:[1] $H^+ {}^-Cl \rightleftarrows H^+ + Cl^-$. Electrolytes which form hydroxide ions, ^-OH, are called bases. Thus, sodium hydroxide and ammonium hydroxide are bases:

$$Na^+ {}^-OH \rightleftarrows Na^+ + {}^-OH$$

$$[NH_4]^+ {}^-OH \rightleftarrows [NH_4]^+ + {}^-OH$$

Salts, like sodium chloride, Na^+Cl^-, the strong acids and the strong bases, are ionized very readily; the weaker acids and the weaker bases are ionized much less readily and, as a result, these are chemically much less active.

The extraordinary speed with which electrolytes react chemically may be demonstrated by the addition of an acid to a base in the presence of a vegetable dye known as litmus, which is red in acidic, blue in basic, and violet in neutral solutions (*Exp.*). Such dyes are called indicators. We notice that the blue color of a sodium hydroxide solution containing some litmus changes instantly to red as an excess of hydrochloric acid is added to it (*Exp.*). In this action H^+ and ^-OH combine to form little ionized water:

$$Na^+ + {}^-OH + H^+ + Cl^- \rightarrow H_2O + Na^+ + Cl^- .$$

Ionization by heat.—Heating and the accompanying fusion of compounds whose molecules contain atoms in ionic union also cause their ionization (*Exp.*) and greatly enhance their reactivity. This is a fact of great importance in geology and in metallurgical processes. Light and other forms of energy cause ionization.

Precipitations.—In ionic actions difficultly soluble substances are often produced and precipitated. Thus, the malodorous hydrogen sulphide of the chemical laboratory precipitates many

[1] The sign $\rightleftarrows$ is used in a chemical equation to indicate that the action occurs in both directions simultaneously. Such a "reversible reaction" will ultimately come to a condition of equilibrium, in which the reaction forming the products on the right side of the equation is exactly as fast as the reverse reaction, in which the products on the right are used to produce those indicated on the left side of the equilibrium sign.

sulphides, such as black lead sulphide from a solution of its nitrate (*Exp.*):

$$Pb^{++} + 2NO_3^{-} + 2H^{+} + S^{=} \rightarrow Pb^{++}S^{=}\downarrow + 2H^{+} + 2NO_3^{-} .$$

Reactions of this kind evidently belong to the class of chemical transformations by processes of exchange. They play a great rôle in natural processes in geology and physiology (for instance, in bone formation).

We may summarize this phase of our discussion as follows: Molecules with atoms held in ionic union are ionizable. They are electric conductors in certain solutions and in the fused condition, and they then react with extraordinarily great speed in chemical transformations.

Non-electrolytes and the electron doublet union; lowered chemical activity.—In contrast to the great activity of atoms in this ionic type of union, we find that atoms linked by electron doublets are very much less reactive, and form more stable compounds. Their chemical reactions such as combinations, separations, exchanges of atoms or of groups of atoms, are usually slow, and often extraordinarily slow.

This very sluggishness of reaction makes for relative chemical stability, combined, nevertheless, with the possibility of slow changes. That is clearly a picture of life-changes—slow indeed, as a rule, but proceeding continually. We shall presently go more deeply into this important phases of our problem.

Naturally, while in extreme cases we can distinguish sharply substances whose atoms are held in molecules in ionic union (as in common salt, $Na^{+}Cl^{-}$) from others whose atoms are held in molecules by the doublet union (such as marsh gas, p. 138), we find frequently combinations of the two types as well as gradual transitions from one type to the other.

Summary.—We have now answered as completely as the occasion permits the first of the three questions we raised some time ago, namely, the question as to the nature of the forces holding atoms together in molecules. They are evidently electrical

forces resulting from the attraction of negative electricity for positive.

We have also answered in part the second question as to why certain elements combine with each other while others are inert toward each other, relations which are often expressed as due to the existence or the absence of chemical affinity between elements. It must be evident from what has been developed in regard to the chemical relations of atomic structures that elements combine when the atoms of the one element by the loss of electrons tend to become positive and the atoms of the other element become negative by the capture of electrons. Thus, we have:

$$4Fe + 3O_2 \rightarrow 2Fe_2^{+++}O_3^{=} .$$

But elements combine and may be held in combination also by sharing electrons; electron doublets unite the positive nuclei of their atoms as in the oxidation of carbon to carbon dioxide (p. 138).

RELATIONS OF ELEMENTS TO ONE ANOTHER

Affinity of elements.—We shall get the most complete answer that our time permits to the question of the sources of the differences in affinity between elements, and at the same time obtain a survey of the behavior of the elements, if we consider now certain general principles which have been found to connect the elements with one another.

The periodic law.—These relations are expressed in the periodic system of elements. In 1869 the Russian chemist, Mendeléeff, gave the world the first complete expression of this profound generalization in the form of the periodic law which, in his own words, stated: "all of the properties of the elements, both physical and chemical, vary as a periodic function of their atomic weights." With the aid of his great generalization, Mendeléeff was able to predict the occurrence of three still unknown elements, their atomic weights, where they probably would be found, and what their properties would be. Within less than twenty years, all three of these elements were discovered.

Again, in the structure of atoms is found the best explanation of the relations expressed in the periodic system. As a first result of this recent advance in knowledge, atomic numbers have been substituted for atomic weights in the statement of the law of the periodic system. The law now may be expressed as follows: The physical and chemical properties of the elements vary regularly and periodically with their atomic numbers. We must limit our elaboration of this law to a discussion of two or three chemical properties only.

Atomic numbers and valence electrons.—In the first place, the atomic number, as we have found, represents the excess of protons over electrons in the nucleus of an atom, that is, the excess of the positive charge on the nucleus. In the second place (except for hydrogen, the element of lowest atomic weight and of atomic number 1), as the atomic number (the positive charge on the nucleus) increases, unit by unit, the number of valence electrons held in the outermost shells of atoms also increases one by one from 0 to 7. When the number of electrons in the outermost shell reaches 8, the electrons are held too firmly to act as valence electrons (see Fig. 20 [*c*]). The number of valence electrons of atoms with an outside shell of 8 electrons is, therefore, again 0. Then the number of valence electrons rises again, with the atomic number, to 7 as before, and so forth. (See col. 4 of Table III.) Here we have the key to the periodic recurrences of properties. In the third place, we have found that chemical combinations of elements and their whole chemical activity depend on these valence electrons (p. 133, etc.). Thus, the increase of valence electrons in the outermost shells of atoms increases the capacity of atoms to develop positive charges from 0 to 7 (called their positive valence) by the loss of their valence electrons, and this increases their capacity to combine chemically with negatively charged atoms in proportion to their charge.[1] (See col. 5 of Table III.)

Further, those atoms which have 4 or more valence electrons

[1] The binding capacity of atoms is the same irrespective of whether they are combined in ionic union or through a doublet. $M^{+}:{}^{+}X$ is evidently equivalent to $M^{+}X^{-}$.

in their outside shells are found to have the capacity to complete their octets by the capture of 4, 3, 2, or 1 additional electrons. These same atoms, through this power, may acquire either 4, 3, 2, or 1 excess negative charges (called their negative valence) and combine in that proportion with 4, 3, 2, or 1 positive charges on other atoms (e.g., $H_2^+O^=$, H^+Cl^-, etc.).[1] (See col. 6 of Table III).

It will be sufficiently accurate for this brief survey to say that those elements whose atoms have the dual capacity to develop valence both by the loss and by the gain of electrons, are also the elements whose atoms show the most pronounced tendency to enter into chemical combination through electron doublets. The other elements, including all the metals, tend toward ionic union, $Me^{+-}X$ in their combinations. Table III illustrates these relations for the elements of atomic numbers 1–20.

Series of elements.—The elements from helium to fluorine, and from neon to chlorine, contained in horizontal lines in the table, are called series of elements. In a series, we note that after we leave the inert elements with zero valence (helium and neon), the atoms of the elements show a growing capacity to combine with oxygen ($R^+{}_2O^=$ to $R^{\ddagger\ddagger\ddagger+}{}_2O_7^=$). In such a series of oxides, it should also be noted that the tendency toward ionic union, and consequently toward ionization, decreases gradually as we proceed from $R^+{}_2O^=$ to $R^{\ddagger\ddagger\ddagger+}{}_2O_7^=$, while the tendency toward doublet union increases. This leads to a gradual decrease of the power of oxides to form hydroxides that ionize as bases, and to a gradual increase in the tendency of the oxides to form acids. There is no sharp break at any point and the two properties overlap.[2]

Similarly, in a series, the first hydrides (Li^+H^-, Na^+H^-, etc.) represent combinations of the ionic type and ionize as salts of hydrogen, in which H^- is the anion, or acid, component. They

[1] These same atoms, capable of completing their octets, may share their electrons in doublet union with other atoms (as in $C(:H)_4$, $H:O:H$, etc.).

[2] Thus, $Na_2^+O^=$ forms with water $Na^{+-}OH$ which is a very strong, highly ionized base; $Al^{+++}(^-OH)_3$ is a much weaker base and shows some weak acidic properties as well.

show great chemical activity. This property also decreases, and when we reach the atoms of elements with at least four valence

TABLE III

ILLUSTRATIVE OF THE RELATION BETWEEN ATOMIC NUMBERS AND THE PROPERTIES OF ELEMENTS*

1 Element and Symbol	2 Atomic Number	3 Atomic Weight	4 No. of Valence Electrons	5 Oxides†	6 Hydrides‡
Hydrogen, H........	1	1	1	$H^{+}{}_2O^{=}$	HH
Helium, He..........	2	4	0	none	none
Lithium, Li..........	3	7	1	$Li^{+}{}_2O^{=}$	$[Li^{+}H^{-}]$
Beryllium, Be.......	4	9	2	$Be^{++}O^{=}$	....
Boron, B............	5	11	3	$B^{+++}{}_2O_3^{=}$	....
Carbon, C...........	6	12	4	$C^{++}_{++}O_2^{=}$	$C\equiv H_4^{+}$
Nitrogen, N.........	7	14	5	$N^{+++}_{++}{}_2O_5^{=}$	$N\equiv H_3^{+}$
Oxygen, O...........	8	16	6	[O:O]	$O=H_2^{+}$
Fluorine, F..........	9	19	7	none	$F^{-}H^{+}$
Neon, Ne...........	10	20	0	none	none
Sodium, Na.........	11	23	1	$Na^{+}{}_2O^{=}$	$[Na^{+}H^{-}]$
Magnesium, Mg......	12	24	2	$Mg^{++}O^{=}$	....
Aluminium, Al.......	13	27	3	$Al^{+++}{}_2O_3^{=}$	....
Silicon, Si...........	14	28	4	$Si^{++}_{++}O_2^{=}$	$Si\equiv H_4^{+}$
Phosphorus, P.......	15	31	5	$P^{+++}_{++}{}_2O_5^{=}$	$P\equiv H_3^{+}$
Sulphur, S..........	16	32	6	$S^{+++}_{+++}O_3^{=}$	$S=H_2^{+}$
Chlorine, Cl.........	17	35§	7	$Cl^{++++}_{+++}{}_2O_7^{=}$	$Cl^{-}H^{+}$
Argon, A...........	18	40	0	none	none
Potassium, K.......	19	39	1	$K^{+}{}_2O^{=}$	$K^{+}H^{-}$
Calcium, Ca.........	20	40	2	$Ca^{++}O^{=}$	$Ca^{++}H_2^{-}$

* The complete periodic system is given at the end of this chapter on p. 159.

† Heavy signs + and − represent ionic charges; light signs + and − represent the relative polarity of doublet union (see p. 139). It will be recalled that ionic and doublet unions often merge into each other. Only the most important characteristics are indicated in the table.

‡ Hydrides like $Li^{+}H^{-}$ represent very reactive unstable salts of hydrogen with ionic union. They are readily decomposed by water (e.g., $Li^{+}H^{-} + H^{+} {}^{-}O.H \rightarrow Li^{+} {}^{-}O.H + H{:}H$) and are to be distinguished from the more common and extremely stable hydrides such as $C(:H)_4$ or $C\equiv H_4^{+}$.

§ See p. 147.

electrons (C, Si, etc.), the hydride formation has become of the doublet type (as in the case of the corresponding oxides) and far more stable hydrides (CH_4, NH_3) result. And, finally, the hydrides become of the ionic type again (H^+F^-, etc.) but ionize as acids, forming H^+ ions. There is no break in the rhythm.

Argon, with zero valence, starts a new series; the next element, potassium, has a single valence electron, like sodium, and the series is continued as before through calcium, etc.

Atomic number.—The predominating influence of atomic number as compared with atomic weight is shown by the consideration of argon and potassium, whose relative positions are determined by their atomic numbers (18 and 19) and not by their atomic weights (40 and 39, respectively). Their chemical and physical characters accord altogether with these positions.

Isotopes.—The supreme significance of the atomic number of an element in relation to its chemical behavior is shown very clearly also by a consideration of the curious discovery that an element may consist of a mixture of varieties of the element called isotopes of the element. The atomic weights of the isotopes of an element are, as a rule, different; their atoms show identical chemical behavior but they often differ in atomic stability.[1]

All of the isotopes of a given element have the same atomic number, that is, the same excess positive charge on the nuclei of their atoms. For instance, chlorine, whose atomic number is 17, consists of atoms of atomic weight 35, whose nuclei contain 35 protons and 18 electrons, as well as of atoms of atomic weight 37,

[1] In 1907 Professor McCoy, in Kent Chemical Laboratory of the University of Chicago, and Professor Boltwood, of Yale University, made the first interesting observations of elements which are chemically inseparable but differ in the weights and stabilities of their atoms. In 1911 Soddy proposed the name isotopes for such elements, and J. J. Thomson in 1913 separated isotopes in atomic quatities by refined physical methods and estimated their atomic weights. In 1914 Richards, at Harvard, proved that lead, formed by the disintegration of uranium, has the atomic weight 206, as against 207 for ordinary lead. Aston undertook the separation of isotopes of neon and finally, isotopes of chlorine have been partially separated on a large scale by diffusion experiments by Professor Harkins, in Kent Chemical Laboratory.

whose nuclei contain 37 protons and 20 electrons; in either case the charge on the nucleus is 17+. Now, the excess positive charge on the nucleus of an atom determines the number of valence electrons held in its outer shell and determines the force with which such electrons are held by the molecule. We thus have 7 valence electrons in the atom of any isotope of chlorine and any atom, capturing a further electron to complete its octet forms Cl^-. All the atoms thus show identical chemical properties. Their occurrence in the form of mixtures of atoms of different weights does affect the atomic weight found for an element. Thus, 35.46, the atomic weight assigned to chlorine, is the average atomic weight of the isotopes of chlorine in the proportion in which they occur in nature in ordinary chlorine and its compounds.

The periodic function and families of elements.—The relations of argon to neon and helium, of potassium to sodium and lithium, etc. (Table III), show why we speak of periodic recurrences of properties. They lead to families, or groups, of elements. Helium, neon, argon, krypton, xenon, and radon form a family with zero valence (see Table IV, p. 159, col. O); the elements are all chemically inert. Lithium, sodium, potassium, rubidium, and caesium form the next family. They are all very active, decompose water, and form easily ionizing, and therefore strong, alkaline bases, $Me^{+-}OH$, and many salts. Their atomic structures[1] show the reason for this resemblance. Thus, we have for the first three elements of the family: Li, atomic weight 7, atomic number 3, a nucleus of 7 protons and 4 electrons, a shell of 2 electrons, and a single valence electron; Na, atomic weight 23, atomic number 11, a nucleus of 23 protons and 12 electrons, shells of 2 and 8 electrons, and a single valence electron; K, atomic weight 39 and atomic number 19, a nucleus of 39 protons and 20 electrons, shells of 2, 8 and 8 electrons, and a single valence electron.

Beryllium, magnesium, calcium, strontium, barium, and radi-

[1] See Fig. 20 (*d*) and (*e*).

um form a similar family of metals, whose atoms lose their 2 valence electrons with great ease and form Be^{++}, Mg^{++}, Ca^{++}, Sr^{++}, Ba^{++}, and Ra^{++} and salts of these ions (see Table IV).

One more family of another kind must suffice, the halogen ("salt-forming") family, comprising fluorine, chlorine, bromine, and iodine (see Table IV, col. VII). Observe the similarity in their outer valence electron shells, which determine their fundamental chemical character: F, atomic weight 19, atomic number 9, with a nucleus of 19 protons and 10 electrons, a shell of 2 electrons and 7 valence electrons. It is the most powerful of all elements in capturing an eighth valence electron, forming F^-. Cl, atomic weight 35[1] and atomic number 17, with a nucleus of 35 protons and 18 electrons, stable shells of 2 and 8 electrons and 7 valence electrons. Its atoms capture the eighth electron with great avidity and form Cl^-. Br, atomic weight[2] 80, atomic number 35, with a nucleus of 80 protons and 45 electrons, stable shells of 2, 8 and 18[3] electrons and 7 valence electrons. Bromine is a powerful agent, but, perhaps because of the distance of its valence electrons from the positive nucleus and because of the intervening stable shells of 28 electrons, its power to capture the eighth valence electron is much weaker than is that of chlorine. Iodine, atomic weight 127, and atomic number 53, has a nucleus of 127 protons and 74 electrons, stable shells of 2, 8, 18 and 18 electrons, leaving 7 valence electrons. Iodine atoms capture an eighth electron, but, as expected, they are the weakest of the halogens in this respect.

Transformation of elements.—The theory of atomic structure also explains why certain elements, like radium, are radioactive, and the principle of the periodic system explains how the chemical characters of these elements change as the elements are trans-

[1] The common atomic weight of chlorine, 35.46, is the average weight of its isotopic atoms in the proportion in which they occur together in nature.

[2] There are isotopes of bromine as of chlorine.

[3] In the heavier and more complex atoms, the electron shells are larger—going from 2 (in helium) to 8, 8, 18, 18, etc., according to Bohr and others. But no shell of more than 8 valence electrons has as yet been found.

formed. The atoms of such elements are very heavy and have unstable nuclei. From the radium nucleus, three helium particles He^{++} (p. 131) shoot out, one after the other, as alpha rays. New elements, radon, polonium, and radioactive lead (an isotope of ordinary lead) are formed in succession. By the loss of the first alpha particle, He^{++}, the excess positive charge on the nucleus is reduced by 2, the atomic number is reduced by 2, and 2 valence electrons of the radium atom are lost. As the radium atom had only 2 valence electrons, radon has none left and is an inert gas like helium, neon, etc., incapable of chemical union with other elements.[1] When radon goes over into polonium and lead, corresponding changes occur. Radioactive lead finally gives off electrons from the nuclei of its atoms as beta rays. The excess positive charge on the nucleus is thus increased by one for each electron lost, and the atom captures an electron for its valence shell and thus increases its valence by one: radioactive bismuth results.

In this connection we may consider very briefly the problem of the transformation of elements by man's own devices. Rutherford and his collaborators have gone farthest in this direction, but only on a molecular scale, not in massive quantities. As a result of the bombardment of atoms of various elements with fast-moving alpha rays, they observed that a number of elements, for instance nitrogen with the atomic weight 14, give off protons (which would form hydrogen by the capture of electrons), while other elements, notably carbon (atomic weight 12) and oxygen (atomic weight 16), do not do so. We note that the atomic weights of carbon and oxygen are whole multiples of 4 and all their protons seem to be held firmly in helium groups. But nitrogen (14), sodium (23), aluminum (27), and other elements of this type have single protons, as shown by their atomic weights, and these protons are more easily lost. Rutherford at first thought that atoms are only disintegrated by this process. Recent experimental results indicate that with very fast moving alpha rays as bombarding particles, the collision of a helium particle He^{++}, say with the

[1] Consult the complete Periodic Table at the end of this chapter in connection with this discussion.

nucleus of a nitrogen atom, may lead not only to the loss of protons, but also to the capture of He^{++} by the nucleus, transforming nitrogen by aggregation as well as by disintegration.

The transformation of elements is a most fascinating problem and is replete with possibilities of the greatest moment in our control of energy and matter.

Early in our discussions, three questions were raised (p. 127). We have tried to outline, as far as space permits, answers of chemistry to two of these questions: first, regarding the nature of the forces holding atoms; and, second, as to the reason why atoms of certain elements combine and others do not.

THE STRUCTURE OF MOLECULES

The third question asked how atoms are arranged in molecules. The study of compounds of carbon—called organic chemistry because the first numerous compounds of carbon were obtained from living or dead organisms—gave us the earliest insight into these relations. It was found that many different substances have the same composition, the same kind and the same number of atoms in their molecules, but show quite different properties. Thus, C_2H_6O is grain alcohol, a liquid boiling at 78°; but C_2H_6O also represents the composition of methyl ether, a gas at room temperature. $C_2H_4O_2$ represents the molecule of acetic acid, the acid in vinegar; of methyl formate, a pleasant-smelling liquid; and of glycole aldehyde, a sweetish solid. Such different compounds of exactly the same composition could only exist if the atoms have definite arrangements in their molecules. We speak of the structure of molecules; water[1] is H—O—H, not H—H—O; alcohol is

$$\begin{array}{ccccccccc} & & H & & H & & & & \\ & & | & & | & & & & \\ H & - & C & - & C & - & O & - & H \\ & & | & & | & & & & \\ & & H & & H & & & & \end{array}, \text{ methyl ether } \begin{array}{ccccccccc} & & H & & & & H & & \\ & & | & & & & | & & \\ H & - & C & - & O & - & C & - & H \\ & & | & & & & | & & \\ & & H & & & & H & & \end{array}, \text{ both } C_2H_6O.$$

[1] Each line or bond — between two atoms represents an electric binding force, either of the ionic type, or, more commonly in carbon compounds, of the doublet type, as we have learned in the preceding discussions.

It is not to be supposed, however, that atoms are rigidly at rest in molecules, as are the stones in a building. No doubt, the individual atoms vibrate around some average position. But any change in the order of attachment or linking of atoms in a molecule produces a molecule of a different substance. Thus, when propyl bromide $\begin{array}{ccccccc} & & H & & H & & H \\ & & | & & | & & | \\ H & - & C & - & C & - & C - Br \\ & & | & & | & & | \\ & & H & & H & & H \end{array}$ (boiling-point 71°) by the action of heat (250°) forms $\begin{array}{ccccc} H & & H & & H \\ | & & | & & | \\ HC & - & C & - & CH \\ | & & | & & | \\ H & & Br & & H \end{array}$ it forms a new substance known as isopropyl bromide (boiling-point 59°).

Space does not permit any elaborate discussion of the experimental methods by which the arrangement of atoms in individually invisible molecules is ascertained. The processes are very much akin to the careful taking apart, say, of an auto engine, the study of each part, and the careful reconstruction of the engine, with the supreme test of performance by the product of reconstruction. Thus, ethyl alcohol, $\begin{array}{ccccc} & & H & & H \\ & & | & & | \\ H & - & C & - & C - O - H \\ & & | & & | \\ & & H & & H \end{array}$, leads to ethane, $\begin{array}{ccccc} & & H & & H \\ & & | & & | \\ H & - & C & - & C - H \\ & & | & & | \\ & & H & & H \end{array}$, and water H—O—H by processes of decomposition (analytical method); it may be prepared again by appropriate methods from ethane and water (synthetic method). Ethyl alcohol resembles water, H—O—H, in essential respects: for instance sodium acts on it, forming hydrogen and sodium ethylate, $H_3C \cdot CH_2 \cdot O^{-+}Na$, which reddens phenolphthalein (*Exp.*) as sodium hydroxide does (p. 122). The structure assigned to ethyl alco-

hol agrees with all of these facts. Methyl ether, $H_3C—O—CH_3$ shows none of this behavior.

The structure of a molecule, determined with the aid of experiment, evidently gives us a concise summary of the chemical behavior of the substance of which it is a molecule.

Space arrangements of atoms in molecules.—We sometimes find that two and even more substances have the same structure, but are of quite different chemical identity. As an illustration, the existence of two lactic acids was observed, one in soured milk, and a different acid, sarcolactic acid, in tired muscles. Both have the structure:

$$\begin{array}{ccccccccccc} & & \mathrm{H} & & \mathrm{H} & & & & & & \\ & & | & & | & & & & & & \\ \mathrm{H} & — & \mathrm{C} & — & \mathrm{C} & — & \mathrm{C} & — & \mathrm{O} & — & \mathrm{H} \\ & & | & & | & & \| & & & & \\ & & \mathrm{H} & & \mathrm{OH} & & \mathrm{O} & & & & \end{array}$$

Lactic acid melts at 18°, sarcolactic acid at 26°. Sarcolactic acid turns the plane of polarized light to the right, ordinary lactic acid has no effect on it. Ordinary lactic acid itself has been resolved further into two acids: the one is identical with sarcolactic acid and the other is so much like it (it also melts at 26°) that the two could easily be mistaken for each other (like twins). The new acid turns the plane of polarized light as much to the left as sarcolactic does to the right. We consider lactic acid, therefore, to be a mixture of dextro-lactic and laevo-lactic acids. Now, these one-sided effects on polarized light—sometimes supported by one-sided crystal structures—led Pasteur in 1860 to the conclusion that differences in the space arrangements of the atoms in molecules underlie these differences in identity. (Incidentally it was to the interest of Pasteur, the chemist, in this very problem that the world owes Pasteur's development later into the founder of modern medicine through his proof of the germ theory of disease. This classic discovery of the separation of racemic acid into dextro- and laevo-tartaric acids led to a call to the University of Lille where he applied himself to a critical study of fermentation.) Finally, in 1874, the Dutch chemist, van't Hoff, and the French chemist, Le Bel, gave us the key to the understanding of these space relations in molecules. They assumed

that atoms are grouped around a carbon atom in the most symmetrical way possible in space, namely, at the four corners of an imaginary regular tetrahedron. Now, we can readily see that a compound like lactic acid $H_3C \cdot {}^*CH(OH)COOH$ with four different atoms or groups attached to the carbon atom C*, could exist in two different space arrangements. These would be mirror images of each other, like our right and left hands; and like these, not superimposable, not identical.

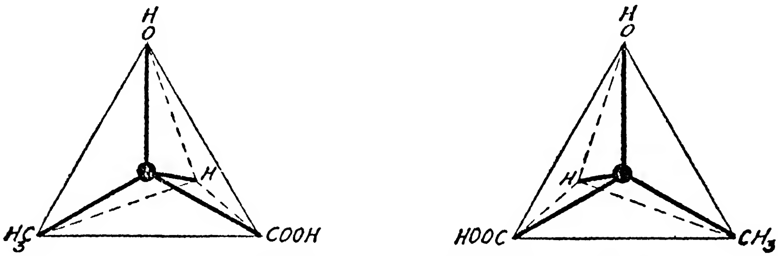


FIG. 22.—Space arrangement of dextro- and laevo-lactic acids.

Space arrangement and chemical activity.—The foregoing results illustrate the modern theory of space arrangements in molecules. It accounts for the possible existence of 16 sugars of the same structure as glucose:[1]

$$\begin{array}{cccccc} \mathrm{H} & \mathrm{H} & \mathrm{H} & \mathrm{H} & \mathrm{H} & \mathrm{H} \\ \mathrm{HC}- & \mathrm{C}^*- & \mathrm{C}^*- & \mathrm{C}^*- & \mathrm{C}^*- & \mathrm{C}\diagdown \\ \mathrm{OH} & \mathrm{OH} & \mathrm{OH} & \mathrm{OH} & \mathrm{OH} & \quad\mathrm{O} \end{array}.$$

Eleven of these are known and for each of them Emil Fischer, in a wonderful piece of deduction from the results of his experiments, determined the arrangement in space. Of these sugars, only 3, d-glucose, d-mannose, and d-galactose, all natural sugars, are directly fermentable and directly available as foods. This fact illustrates the importance of these relations for a thorough understanding of the chemistry of life.

Applications of the knowledge of the structure of molecules.—The knowledge of the structure of cocaine, valuable as a local

[1] The four carbon atoms C* are asymmetric and we have 2^4 or 16 possible arrangements in space according to this theory

anesthetic in surgery, gave to chemistry the opportunity to improve on nature's own product and to prepare for medicine simpler, less toxic, but similar, artificial local anesthetics such as procaine, butyn, etc. These have the further great advantage over cocaine that they are not at all habit forming. In time, man will be able to dispense entirely with the pernicious natural drug. Similar work on vital physiologic products forms a basis for progress in physiology and other branches of biology.

Now, the length of carbon chains and their relative, but not absolute, stability makes possible in a very simple way an accumulation of different properties in a single molecule, which is of very great importance in life. Thus, one of the many constituents of protein is cystin, $HS\text{–}CH_2\text{–}CH(NH_2)CO\text{–}OH$. The amine group ($NH_2$) gives cystin basic functions, or the power to combine with acids, which ammonia NH_3 possesses; the COOH group gives it acid properties with power to combine with bases. The basic part combines also with the acid part, forming an internal salt. Hence, cystin is base, acid, and salt—all in one! Moreover, the SH group makes it easily susceptible to oxidation to cystein, $HOOC\text{—}CH(NH_2)CH_2S\text{—}SCH_2CH(NH_2)COOH$, a reaction which makes it and similar products important factors in the oxidation processes of cellular life.

Proteins.—Most important of all, the simultaneous presence of the amino group NH_2 and the acid group COOH in the amino acids (of which cystin is a representative) makes it possible for many molecules of different amino acids to combine and form single molecules of the type:[1]

$$\begin{array}{l} H_2N\underset{\displaystyle R_1}{\underset{|}{C}}HCO\cdot NH\underset{\displaystyle R_2}{\underset{|}{C}}HCO\cdot NH\underset{\displaystyle R_3}{\underset{|}{C}}HCO\cdot NH\underset{\displaystyle R_4}{\underset{|}{C}}HCO\cdot NH\ \ldots\ldots \end{array}$$

This is the characteristic structural type of proteins. When we digest proteins, the large molecules take up water under the influence of digestive enzymes, such as pepsin (*Exp.*), and acid or al-

[1] R_1—, R_2—, R_3—, etc., represent different organic "radicals," i.e. groups of carbon, hydrogen, and other atoms.

kali, and break down between the CO and the NH groups at the "joints" marked •, forming amino acids $RCH(NH_2)COOH$. These are absorbed by our bodies and used to build up proteins we need.

Sørensen has found the molecular weight of egg albumin to be approximately 34,000, of serum albumin about 45,000, and of serum globulin from about 80,000 to about 140,000. In egg albumin perhaps 200 or more molecules of various amino acids are combined into a single large molecule by the loss of water.

This extraordinary increase in molecular weights is attended by important results, only two or three of which space permits us to mention: (1) The physical properties change from ready solubility in water to slight solubility, and give to proteins the properties of colloids,[1] making possible the formation of membranes and of other organic structures characteristic of biologic forms. (2) It is evidently possible to concentrate into a single protein a most impressive variety of characteristic properties. (3) It is also clear that with hundreds of molecules of various amino acids condensed into single molecules, provision is made for an extraordinary variety of proteins, in a way that must make proteins of significant importance in biology. Each species has its specific proteins, the injection of which into an animal of a different species often causes the most violent reaction and even death (by anaphylactic shock). Modern thought is, indeed, inclined to look to the chemistry of proteins to help advance the study of such great problems as heredity and its many implications.

CHEMICAL ACTION AND ENERGY

Oxidation of organic compounds.—Life, animal life in particular, is a process which demands also the ability of the body to break down by oxidation the long carbon chains of the molecules of our foods, the sugars, proteins, etc. This internal combus-

[1] Amorphous gelatinous bodies such as gelatine and glue were distinguished by Graham as "colloids" from such "crystalloids" as sugar, salt, etc. Colloids are only very slightly soluble, they form suspensions and emulsions, and under certain conditions absorb and hold large amounts of water. They do not pass readily through membranes.

tion with the aid of the oxygen of the air keeps us warm, makes motion and work possible, and gives us the necessary energy for our body functions. Plants absorb the energy of the sun's rays and build up the complex molecules of our foods; they, and the animals feeding upon them, provide us with our sustenance. How do we manage to break down carbon chains which are often so stable that starches have been known to persist through thousands of years in kernels of grain found in ancient tombs?

Oxidation, an electric process.—The key to the answer to this question, so profoundly important for our understanding of life, is again found in the electric structure of matter. Stable carbon chains are made up of links of carbon atoms firmly held by doublet electrons. But through partial oxidation of carbon atoms, they become more and more polar, and decided polarity of two neighboring carbon atoms makes their separation easily possible. This, of course, is in harmony with the ready breakdown of the extreme polar or ionic union, as in Na^+Cl^-. Ethane, $(H:)_3C:C(:H)_3$, is extremely stable—our bodies are utterly incapable of consuming it or similar paraffins. But oxalic acid, with two largely polar carbon atoms, is easily oxidized to carbon dioxide (*Exp.*):

$$HOOC : COOH + Mn^{++++}O_2^{=} \rightarrow 2CO_2 + Mn^{++}O^{=} + H_2O \ .$$

The doublet escapes into the Mn^{++++} ion, causing the breakdown of the oxalic acid with the formation of carbon dioxide, water, and the lower oxide of manganese.

When we oxidized hydrogen or iron, we were able to obtain an electric current by transferring their electrons to oxygen through wires (p. 136). The escape of the electrons from oxalic acid may be shown in the same way (*Exp.*).

We shall also try this experiment with formaldehyde, CH_2O or $H_2{}^{+}::\ddagger C \ddagger \overline{\underline{}}O$ from which the plants prepare glucose, $C_6H_{12}O_6$, starches $(C_6H_{10}O_5)_x$, and proteins for us. There are two electron doublets which can escape. Will they escape to oxygen, which we use in our blood? We see that we have at best a very faint effect

(*Exp.;* see Fig. 21, p. 136). But now, when we add alkali[1] to the formaldehyde and make the solution alkaline, as is shown by the red color of added phenolphthalein, we observe an extraordinary increase in effect—electrons are now flowing at a high rate from the molecules of the formaldehyde through the wires to the oxygen atoms. Our blood is somewhat alkaline; acidosis destroys us. Our body oxidations are carried out, as here, at low temperatures and, in health, as here, with remarkable efficiency.

Chemical action and changes of energy.—One last consideration must be dwelt upon. When a flash of lightning passes from a charged cloud to a tree, a tremendous amount of energy is released. When two groups of atomic aggregations such as iron (or carbon) and oxygen react chemically and electrons pass from iron (or carbon) to oxygen and chemical transformation occurs, a large amount of energy is similarly released: the white heat we see developed when iron or carbon burns in oxygen is a measure of the energy available in such actions. The energy in carbon (coal) and oil runs steam engines and does the greater part of the world's work. A few moments ago we saw the chemical energy stored in our chemicals released as electrical energy; formaldehyde against oxygen developed an electric current which lifted the needle of the galvanometer. All electrical batteries function through the release of chemical energy in the form of working electrical currents. Vice versa, the power of a Niagara is converted into electrical energy and used to separate elements knit together in chemical union; the energy is thus stored in the elements separated. Aluminium is pried loose from oxygen by electrolysis; chlorine is released from sodium in common salt, and is used for bleaching, the disinfecting of drinking water, and other purposes.

Conclusion.—The outline of the nature of chemical processes which we have followed is our picture of chemical thought of today. As our knowledge grows, theories and facts will come into sharper focus and give a clearer, truer picture. But even today, in-

[1] The effect of the alkali is explained, pp. 289–93 of Stieglitz, *Qualitative Analysis* (Century Co., 1911), Vol. I.

complete as it is, the science of chemistry has given man a mastery over forces controlling his life, in biology, in medicine, and in industry, which contributes generously to the health and the safety, the comfort and the happiness, of the people of this world.

TABLE IV

PERIODIC TABLE ACCORDING TO ATOMIC NUMBERS, H:1

Period	O	I A B	II A B	III A B	IV A B	V A B	VI A B	VII A B	VIII
1	2 He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	
2	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	
3	18 A	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe 27 Co 28 Ni
		29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	
4	36 Kr	37 Rb	38 Sr	39 Y	40 Zr	41 Cb	42 Mo	43 Ma	44 Ru 45 Rh 46 Pd
		47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	
5	54 Xe	55	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Il	
		62 Sa	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	
6		69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os 77 Ir 78 Pt
		79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 ?	
7	86 Rd	87 ?	88 Ra	89 Ac	90 Th	91 Bu	92 U		

NAMES OF THE ELEMENTS

1. Hydrogen
2. Helium
3. Lithium
4. Beryllium
5. Boron
6. Carbon
7. Nitrogen
8. Oxygen
9. Fluorine
10. Neon
11. Sodium (Natrium)
12. Magnesium

NAMES OF THE ELEMENTS—*Continued*

13. Aluminium	40. Zirconium	67. Holmium
14. Silicon	41. Columbium	68. Erbium
15. Phosphorus	42. Molybdenum	69. Thulium
16. Sulphur	43. Masurium	70. Ytterbium
17. Chlorine	44. Ruthenium	71. Luticium
18. Argon	45. Rhodium	72. Hafnium
19. Potassium (Kalium)	46. Palladium	73. Tantalum
20. Calcium	47. Silver (Argentum)	74. Tungsten (Wolfram)
21. Scandium	48. Cadmium	75. Rhenum
22. Titanium	49. Indium	76. Osmium
23. Vanadium	50. Tin (Stannum)	77. Iridium
24. Chromium	51. Antimony (Stibium)	78. Platinum
25. Manganese	52. Tellurium	79. Gold (Aurum)
26. Iron (Ferrum)	53. Iodine	80. Mercury (Hydrargyrum)
27. Cobalt	54. Xenon	
28. Nickel	55. Cesium	81. Thallium
29. Copper	56. Barium	82. Lead (Plumbum)
30. Zinc	57. Lanthanum	83. Bismuth
31. Gallium	58. Cerium	84. Polonium
32. Germanium	59. Praseodymium	85.
33. Arsenic	60. Neodymium	86. Radon
34. Selenium	61. Illinium	87.
35. Bromine	62. Samarium	88. Radium
36. Krypton	63. Europium	89. Actinium
37. Rubidium	64. Gadolinium	90. Thorium
38. Strontium	65. Terbium	91. Brevium
39. Yttrium	66. Dysprosium	92. Uranium

SELECTED REFERENCES

There are a number of excellent books which illustrate in an intelligible form many important applications of chemistry to industry and medicine. The existence of such books has made it possible to confine our discussions to the development of basic principles only. Every student should read at least chapters i, ii, iii, and xiii, or xiv of *Creative Chemistry* by E. E. Slosson (Garden City Publishing Co., Garden City, N.Y.) before studying this chapter.

Other illustrative books recommended are: *Chemistry in Industry* (2 vols.), *Chemistry in Agriculture*, and *The Future Independence and Progress of American Medicine in the Life of Chemistry* (The Chemical Foundation, New York). McCoy and Terry's *Introduction to General Chemistry* (New York: McGraw-Hill Book Co.) or Schlesinger's *General Chemistry* (Longmans, Green & Co.) are recommended as books of reference on principles of chemistry.

CHAPTER VI

THE NATURE AND ORIGIN OF LIFE

HORATIO HACKETT NEWMAN

I. LIFE—ITS NATURE AND MANIFESTATIONS

INTRODUCTORY STATEMENT

The relation of biology to other sciences.—It is customary to classify the natural sciences into three categories: (*a*) the earth sciences, including geology, geography, paleontology, and certain aspects of astronomy; (*b*) the physical sciences, including physics and chemistry; (*c*) the biological sciences, including botany and zoölogy, together with the various specialized branches of these two, such as morphology (the science of structure), physiology (the science of function), taxonomy (the science of classification), genetics (the science of origins), and a host of others.

Biology is profoundly indebted to the physical sciences and could make little progress without employing the laws and principles of those fundamental sciences. The earth sciences and the biological sciences are intimately interdependent, for earth history has been deeply affected by living organisms, while living organisms have been adaptively modified in accord with changes of the earth's surface.

One of the objects of this book is that of making clear the basic oneness of all science, and perhaps nowhere is this conception more clearly exemplified than just here. All natural science concerns itself with transformations of matter and of energy. The difference between one group of sciences and another is largely one of levels or thresholds—in a sense also of units of greater or less inclusiveness. Astronomy deals with the largest material units, such as galaxies, solar systems, and planets; with the largest space units such as light-years; and with time units of billions of years. Geology concerns itself chiefly with one astro-

nomical unit, the earth, but overlaps upon astronomy in dealing with the origin of the solar system and upon chemistry in dealing with the chemical composition of the rocks; its space units are miles and its time units millions of years. Chemistry and physics share the domain of molecules, atoms, and electrons, and make use of such time units as minutes and seconds, even fractions of seconds. With what level, or threshold, of matter and energy transformations does biology deal? There is a certain order of changes, far above the atomic or molecular level, far below the cosmic or the geologic level, differing intrinsically from these, but of a part with all of them, a level that for want of a better term we speak of as organic. The units of biology are organisms—a word implying definitiveness of arrangement, complexity, orderliness. It is essential, however, for us to realize that the orderliness of the organism is not an isolated orderliness, but simply one aspect of the universal orderliness of nature. The whole non-living universe may be thought of as the background, or the conditioning environment, of living organisms. With a different environment organisms would undoubtedly be different from those with which we are familiar. The orderliness so manifest in the realms of astronomy, of geology, of physics and chemistry, affords the material setting of life. It is far from our thought, however, to put life on a pedestal and consider it something transcendent or extra-natural, for to look upon life in this way is fatal to understanding and to progress. Only when we realize that life is part and parcel of the physical universe can we begin to approach an understanding of its nature and its significance.

It is the plan of the present chapter to propound several fundamental questions about life and either to attempt to answer them or else frankly to admit that, with knowledge in its present state, they cannot yet be answered. These are the questions that demand an answer:

1. What is life?

2. In what ways is living matter similar to non-living matter and in what ways is it different?

3. Is it possible to understand the manifestations of life in terms of the laws of energy and of matter?

4. With what thresholds, or levels, of natural phenomena is biology concerned?

5. What are the units of life?

6. What is the basis of unity of organization, or of individuality?

7. How is life perpetuated?

8. How does the complex organism come into being?

9. How did life originate on the earth?

10. What is the theory of organic evolution?

11. Has this theory been scientifically proved?

12. What are the methods by means of which the validity of the theory has been established?

WHAT IS LIFE?

The mystery of life.—It has long been customary in certain circles to characterize life as "the mystery of the universe," but to the scientist there is no greater mystery about life than there is about energy or about matter. The "mystery" of life is much the same as the "mystery" of light or of electricity: we cannot exactly define any of them, but know them chiefly through their manifestations.

Attempts to define life.—If we could give a concise and readily intelligible definition of life, much of the "mystery" would disappear, for mystery consorts only with the undefined. Any number of attempts have been made to define life, but all fall short of their purpose in that they evade the issue or else fail to include many essentials. Examples of definitions that evade the issue are as follows: (*a*) "Life is the state of living"; (*b*) "Life is the sum total of vital functions." Examples of definitions that are true as far as they go, but lack inclusiveness, are those of Spencer and Lewes. "Life," according to Herbert Spencer, "is the continual adjustment of internal relations to external relations." G. H. Lewes defines life as "a series of definite and successive changes

both in structure and in composition, which take place in an individual without destroying its identity." These are probably the best definitions of life that have been devised, yet they all leave the reader without any conviction that the definers really know exactly what life is. The truth of the matter is that, in the first place, life is too complex to be defined in concise and simple terms; that, in the second place, it is unique and, therefore, it cannot be defined by analogy or by comparing it with something else; that, in the third place, it cannot readily be defined by contrast, as there is nothing exactly antithetic to life. Death is not the antithesis of life, for it merely involves the cessation of life. Since, then, we cannot define life directly and simply, we must resort to a complex and roundabout definition, consisting of a description of its chemical and physical constitution and of some of its characteristic manifestations. But before we can intelligently discuss the properties of living matter, it will be necessary to state our general stand on a matter of very fundamental importance.

Mechanistic versus vitalistic views.—There are two opposed biologic philosophies: one known as the vitalistic view, or vitalism, the other as the mechanistic view. The vitalist is more or less of a mystic in that he believes that life involves "some all-controlling, unknown and unknowable, mystical, hyper-mechanical force." In its milder forms vitalism may be defined, according to Woodruff,[1] as "the conception that life phenomena are in part at least the resultant of manifestations of matter and energy which transcend and differ intrinsically in kind from those displayed in the inorganic world." This conception is tantamount to a denial that the laws of energy and of matter are sufficient to account for biological phenomena. Such a view is exactly opposite to those which have led to all the scientific progress that has been made. The introduction of mystical forms of matter and energy without any justification in experience is characteristic of an age that is, happily, largely outgrown.

~~The~~ mechanistic point of view ~~is one that assumes as a working~~

[1] See No. 4 in "Selected References" at end of chapter.

~~hypothesis that~~ life is an expression of the transformations of energy and of matter in a large group of materials, differing in detail, but alike in certain fundamental respects—materials known technically as protoplasmic and which constitute what Huxley termed "the physical basis of life." Life has never been observed except in some kind of protoplasm, and, therefore, must be due to the physical, chemical, and organizational properties of these substances. When used as a working hypothesis, the mechanistic principle has amply justified itself. It is the foundation-stone of functional biology (physiology); it is proving its worth in comparative and in human psychology; and it forms the background of experimental medicine. So long as a hypothesis is fruitful in unlocking the secrets of nature it is doing all that could be asked of it. No wonder, then, that modern biology is so frankly mechanistic and so inhospitable toward vitalism! A moderate and generally acceptable statement of the mechanistic position was made about fifteen years ago by Professor D'Arcy W. Thompson:

> While we keep an open mind on this question of vitalism, or while we lean, as so many of us now do, or even cling with a great yearning, to the belief that something other than physical forces animates the dust of which we are made, it is rather the business of the philosopher than of the biologist, or of the biologist only when he has served his humble apprenticeship to philosophy, to deal with the ultimate problem. It is the plain bounden duty of the biologist to pursue his course unprejudiced by vitalistic hypotheses, along the road of observation and experiment, according to the accepted discipline of the natural and physical sciences. . . . . It is an elementary scientific duty, it is a rule that Kant himself laid down, that we should explain, just as far as we possibly can, all that is capable of such explanation, in the light of the properties of matter and of the forms of energy with which we are already acquainted.

Following this admonition we shall now proceed to a frankly mechanistic analysis of that peculiar material known as protoplasm, that substance which possesses the properties whose sum total spells L-I-F-E. This is our roundabout method of defining life: to describe as many as possible of the distinguishing characteristics of living matter as opposed to lifeless matter, and to

note its most fundamental manifestations. We ~~shall~~ can consider the properties of protoplasm under eight different heads: chemical composition, physical properties, metabolism, growth, reproduction, rhythmicity, irritability and conductivity, adaptability. but we shall now discuss only those which are similar in plant and human life.

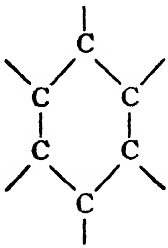
THE EIGHT CHARACTERISTICS OF PROTOPLASM

I. CHEMICAL COMPOSITION

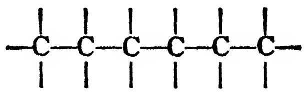
If the chemist who first made an analysis of protoplasm hoped to discover some new or unique vital element, he was doomed to disappointment, for he found nothing new nor even unusual. On the contrary, the decomposition products of protoplasm consist of nothing but the commonest elements in the world: carbon, hydrogen, oxygen, nitrogen, sulphur, phosphorus, chlorine, sodium, potassium, calcium, magnesium, and sometimes traces of iron, manganese, iodine, silicon, and copper. No material is present in living protoplasm that leaves it when death ensues, for a given bit of protoplasm weighs exactly the same after death as when alive. Moreover, it is certain that no special life element escapes during the process of analysis, for the weight of the recovered elements exactly equals that of the original living material.

Since, therefore, living matter does not differ at all from lifeless matter in its contained elements, in what lies the difference between them? It might be answered that there are certain compounds of these elements that are peculiar to living substance. This is true only to a limited extent, for some of these compounds have been synthesized in the chemical laboratory and somewhat similar substances occur elsewhere in nature. There are three types of these carbon compounds that are especially characteristic of protoplasms: carbohydrates, fats, and proteins. Carbon seems to be the key element in these protoplasmic compounds; it has certain special properties that make it more suitable than any other element for its vital rôle. Among other things, it has a strong tendency to form chains, rings, and spirals of carbon atoms

linked directly together. This is due to the very strong tendency of these atoms to form doublet unions (see p. 137). For some unknown reason carbon atoms seem to hold together more firmly in groups, or galaxies, of six than in larger or smaller groups. The six carbon atoms may unite to form the relatively stable closed ring, known as the aromatic galaxy (*A*, below), or they may remain in the form of a loose-ended series, the aliphatic galaxy (*B*, below), which is much more labile. Carbohydrates, fats, and proteins are all derivatives of the aliphatic galaxy.

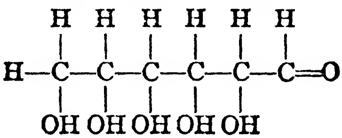


A



B

Carbohydrates.—The simplest common carbohydrate is the sugar, glucose, which has the following molecular structure:



A more complex sugar may be made by setting free an H atom from one molecule and an OH group from another molecule, and then uniting the rest into a double molecule. The freed H and OH unite to form one molecule of water. By further dehydration and welding we can get much more complex sugars, and after these, starches and celluloses. It takes two hundred glucose molecules to make a molecule of starch.

All these substances are manufactured in plant cells out of such simple materials as CO_2 from the air and H_2O from the soil, under the influence of sunlight. How the plants accomplish this

is described in a subsequent chapter under the head of "photosynthesis" (p. 253).

Fats. –Fats and oils are rather more complex than are carbohydrates. They are compounds of glycerol and some of the higher fatty acids, such as butyric, stearic, and palmitic acids. The glycerol part of fats is manufactured in the organism from the simple carbohydrate, glucose. The fatty acids are also believed to be derived directly or indirectly from carbohydrates. Consequently, the ingredients for fat production are ready at hand in both plants and human living ~~animals~~. Omitting the chemical details of how complex molecules of fats, oils, and allied substances known as lipoids are built up, let us merely note that the differences between the numerous fats depend on the particular kind of fatty acid employed. Some fats are compounds of two or more different fatty acids combined with glycerol. A few of the best-known fats are lard, tallow, and butter from animals, and cocoanut oil, olive oil, and castor oil from plants.

The particular significance of fats as part of living substance is that they have a very high energy content, more than twice that of carbohydrates. They, therefore, are well adapted to the function they most commonly subserve, that of maintaining in cells food reserves to be used in emergencies.

Proteins.—Proteins are characterized by the immense complexity of their molecules, and they are distinguished from other protoplasmic components in that they always contain nitrogen and usually phosphorus, sulphur, and iron. The starting-point for the manufacture of proteins in the bodies of organisms is the same as that of fats, i.e., various fatty acids. By substituting nitrogen in the form of amino (H—N—H) for one of the H atoms, a type of compound is formed known as an amino acid, of which many kinds are known. These amino-acid molecules are called the building-stones of proteins, for by welding them together chemically by a process known as dehydration, vast molecules are built up some of which are known to consist of several thousand atoms.[1]

It should also be noted that there is an almost endless variety of patterns into which the various amino-acid building-stones can be arranged, and every different arrangement gives a different substance with different properties. This helps to explain how it is that every species of organism has its own peculiar specific set of proteins, and that every individual is doubtless as peculiar in its proteins as in its visible structural characters. Such a conception is of very great interest in connection with heredity, for it is generally believed that the determiners of definite hereditary differences are specifically different proteins.

The chemistry of proteins is a difficult subject and too technical for presentation here. We shall merely call attention to one more of the characteristics of these remarkable substances—their instability or lability. By this is meant that they undergo relatively great physical and chemical changes under relatively slight provocation. This accounts in part for the phenomenon of irritability so characteristic of protoplasms.

While chemists have been able to synthesize many of the carbohydrates and fats, they have never been able to make up artificially any of the true proteins, though one of the striking advances of modern chemistry consists of the synthesis of certain compounds of amino acids known as polypeptids, substances closely similar to proteins.

Water.—Water might appropriately be ranked first among protoplasmic ingredients, for it makes up from 65 to 97 per cent of the total weight of protoplasm. Protoplasmic activity depends—like most forms of chemical activity—on abundant water. The removal of water, although at first slightly stimulating, has a pronounced depressing effect, which becomes progressively more marked with continued desiccation until dormancy results, as in dried seeds. The addition of water then allows the vital processes to proceed, as when a seed germinates.

Salts.—Salts in solution in the more fluid parts of the protoplasm are as essential as anything else for normal life. The commonest salts in protoplasm are those of sodium, potassium, cal-

cium, magnesium, iron, and manganese. These basic atoms are found in rather fixed and definite concentrations, and they have the power of neutralizing and balancing one another and of regulating the normal chemical equilibrium of the organism.

Summary of chemical composition.—We have given a brief account of the substances which may be called the disintegration products of protoplasm. A mixture of all of these substances, however, would not make protoplasm, for such a mixture would not be alive. All of these substances, in fact, are found in the blood and can be made to play their normal rôle outside of living organisms. In order to have life the components of protoplasm must be organized in a very definite fashion. This we shall discuss in a later connection.

2. THE PHYSICAL PROPERTIES OF PROTOPLASM

Active living protoplasm, whether that of animals or plants, whether of man or the lowliest organism, appears to the naked eye, or to the eye aided by the compound microscope, as a semifluid or viscous material, sometimes colored but commonly practically colorless and almost transparent. When examined under the highest available magnification it reveals itself as a more or less complex mixture of different ingredients such as granules, fibers, droplets of liquid, imbedded in a more or less structureless ground-substance, or matrix. All of the ingredients of such a mixture are to be thought of as integral parts of the living mixture we call protoplasm. There is an orderliness about the disposition of materials in this mixture which is an expression of the factors that underlie unity of organization.

From the purely physical standpoint protoplasms are colloidal mixtures, the mixture sometimes being so intimate as to constitute an emulsion. These terms need explanation. A colloid is a substance with a gluelike consistency, lacking crystalline structure and incapable of going into ordinary solution in certain solvents. When mixed with a solvent such as water, the molecules do not separate nor break up into ions, but they remain aggre-

gated into discrete masses of material of considerable size merely suspended in the medium. Colloidal particles range from those visible to the unaided eye to those no larger than some single molecules.

When the particles are densely packed together the material sets, becomes more or less rigid, and is in the *gel* state; but when the particles are separate from one another, the material resembles a solution and is in the *sol* state. Thus solid gelatin (the gel state) may become first a viscous semi-fluid and then a thin, watery fluid as the particles are driven farther apart by the addition of water, by heat, or by the addition of chemicals. Colloids readily pass back and forth from the sol to the gel states. In some cases the change goes equally readily both ways, but in other cases the change goes readily in one direction, but is very difficult to reverse. Thus it is easy to coagulate egg-white by means of heat, but very difficult (though not impossible) to bring it back to the sol state. It may be stated here that many of the rhythmic changes to be mentioned later, such as ciliary action, heart beat, and rhythmic processes in cell division, are probably based upon reversible changes in colloidal state.

Most protoplasmic colloids belong to a category known as emulsoids. In this state the suspended particles are relatively stable, are less easily coagulated by salts than are simple colloids, are commonly viscous, tend to form surface membranes, and show a high capacity for more or less rhythmic reversals of colloidal state. All of these properties will be recognized as characteristic of living matter, yet they are known to be but the physical properties of certain forms of matter in the colloidal state.

Colloidal chemistry is an advanced and highly specialized subject—far too technical to be discussed here. It should be borne in mind, however, that in this field of research lie many clues pointing toward a solution of some of the most obscure problems of present-day biology.

This very brief analysis of the physico-chemical constitution

of living matter must suffice for the present. If we have succeeded in showing that the living material, collectively known as protoplasm, is, even at its simplest, an intricate yet orderly mixture or emulsion of colloids and crystalloids in an aqueous medium, and that the laws of physics and chemistry applicable to such complexes are already fairly well understood, we have accomplished as much as we can hope for at this time.

3. METABOLISM الأيض وبناء [illegible]

One of the very characteristic properties of protoplasm is its ability to maintain itself by borrowing materials and energy from its surroundings. The specific protoplasm of any organism is able to take up from its environment foreign proteins, carbohydrates, and fats, to break these up into simpler compounds, and to rebuild these materials into more of its own particular kinds of protoplasmic ingredients. Living protoplasm is also able to use up its own substance, chiefly by processes of oxidation, and in so doing to release energy in the form of heat, light, electricity, or mechanical motion, at the same time producing chemical substances less rich in energy. This is sometimes known as waste and repair, but a better term for the whole cycle, from inorganic material back to inorganic material, is metabolism. The building-up phase is known as anabolism and the breaking-down phase, katabolism. Both processes go on simultaneously all the time in active protoplasm. In the total absence of food the anabolic phase is held in abeyance, though for a time the stored food products may be used to build up more essential elements of the protoplasm. In young organisms anabolism exceeds katabolism and an accumulation of material results. This involves increase in size, or growth. In old age the katabolic phase of the cycle gains the ascendency, and a wasting away of living matter takes place which, if carried too far, results in serious disturbances of equilibrium and ultimately in death.

The most striking fact about metabolism, however, is that individuality is maintained throughout life in spite of the fact

that the actual chemical constitution of living substance is constantly changing.

Metabolism is a general term including all transformations of matter and of energy in the organism. The metabolic rates of different individuals, species, or larger groups of organisms differ, and there are differences of metabolic rate in different parts of the same organism, as we shall bring out in our discussion of the organization of living matter. The metabolic rate of an organism may be measured in terms of heat production, oxygen consumption, carbon-dioxide production, and in other ways.

The question arises whether metabolism is a unique property of living matter or whether equivalent processes go on in lifeless materials. A common parallel to metabolism is the candle flame. If allowed to burn in a quiet atmosphere, the flame, with its central colorless core, its luminous zone, and its outside zone of carbon dioxide and water vapor, remains constant in form and structure in spite of an ever-changing content. It is constantly taking in new materials, transforming them into flame, and giving off products of combustion and energy in the form of heat and light. Why is this not fully an example of metabolism? Certainly the analogy is very close, and if the ability to do this kind of thing were the sole criterion of life, the candle flame would be alive. But can the candle flame grow and reproduce other candle flames like itself?

4. GROWTH

One of the properties of living substance is its ability to grow or increase its mass. When anabolism exceeds katabolism, growth is inevitable. Growth is one phase of development. In order that a young animal of small size may become an adult it must not only grow, but it must become differentiated, i.e., it must become more complex and special tissues must be developed for the more expert performance of different functions. These matters are more definitely a part of the phenomenon of development, however, and will be dealt with in a subsequent connection.

Growth proper is a mere matter of increase in mass. There are very distinct limits to the size any given kind of organism may attain. In some micro-organisms the size of the individual is so small as to make them nearly or quite invisible even with the best microscopes, while some of the whales grow to be larger than a freight car. Whether large or small, there is a definite size limit for each species. We do not know yet just what factors are responsible for specific size limitations. When, however, the maximum size is reached the organism may remain in a state of equilibrium for a considerable time, or it may divide to form offspring.

5. REPRODUCTION

All individuals are mortal. Some individuals, such as the giant sequoias, may have a life span of thousands of years; other individuals, such as unicellular organisms, may live only for a day or an hour. It stands to reason, then, that if life is to continue on the face of the earth, new individuals must be produced. The only way in which new individuals are known to arise today is through reproduction from previous individuals. Reproduction is essentially a process of making an offspring out of a part of a parent. Sometimes the process seems extremely simple, almost crude, as in binary fission. In this process the parent individual merely divides into two approximately equal halves, each half of which then becomes a new individual capable of growing to the size of the parent and attaining its characteristic features. Fission is a primitive method of reproduction and is utilized by nearly all of the lowest organisms as well as by many relatively high groups, such as the segmented worms. A special form of fission, extremely common in plants and characteristic of some of the lowest animals, is sometimes called multiple fission and sometimes sporulation. The result of sporulation is the production of reproductive cells called spores, which, when isolated from the parent body, are able to produce new individuals.

Budding is another relatively simple reproductive method, widely used among animals and almost universal among plants.

It differs from fission largely in the fact that, whereas in fission the identity of the parent is entirely lost, in budding the main part remains essentially unchanged, and only a minor part or parts are cut off as offspring.

Germ-cell reproduction in the higher organisms involves the separation from the parent body of minute representative parts, single cells, that leave the parent body essentially unchanged. These specialized cells (gametes) usually unite in pairs in a process known as fertilization, in which a minute sperm cell enters or fuses with a relatively large egg cell to form a zygote, which is essentially a new individual at the beginning of its career. As the reproductive processes are to be dealt with in subsequent chapters and will there be explained in much greater detail, let it be sufficient here to have shown that reproduction of some sort is an essential characteristic of living things and a direct consequence of growth and development.

6. RHYTHMICITY

Just as there are cosmic rhythms, geologic rhythms, atomic and molecular rhythms, so there are vital rhythms as well. In fact, the rhythmic, or cyclic, character of vital processes is one of their most distinctive features. There is the metabolic cycle, the rhythm of generations in reproduction, the rhythm of cell division, the rhythm of the heart beat, and other rhythms too numerous to mention. Most of the processes of change in the universe are rhythmic, or periodic, and life-processes constitute no exception to the rule. The underlying basis of rhythmicity is at present obscure—not even approximately understood. All we need do here is to note its prevalence as a characteristic of life and some of its most obvious expressions.

7. IRRITABILITY AND CONDUCTIVITY

Another of the most striking characteristics of protoplasm is its irritability, that is, its ability to respond by growth, movement, or in some other way to various kinds of stimuli, internal or external. The basis of irritability is probably the chemical

and physical instability of the complex protoplasmic mixture. Local responses to stimuli may be in the form of direct contraction, direct secretion, direct growth changes; more commonly, however, stimuli affecting one region, such as a sensory cell, affect not only the region stimulated, but are transmitted through the general protoplasm (or through special transmitting structures such as nerve fibers) to other parts capable of responding by modifications of a chemical or physical character. This is probably the basis of the maintenance of individuality in organisms, of nervous co-ordination, and of adaptive behavior.

8. ADAPTABILITY

Protoplasm in responding to environmental stimuli seems generally to do so in such a way that the change is an appropriate response to the stimulus, whether the response be structural, chemical, or merely a movement of some sort. Changes that are of advantage to the organism and tend to keep it adjusted to its environment are known as adaptive changes. One of the outstanding peculiarities of protoplasms is their capacity to modify themselves in appropriate ways under the influence of changes in the environment. No more need be said about this important phenomenon here, for it is to be dealt with at length in subsequent chapters (chap. ix and pp. 253–55).

THE UNITS OF LIFE

Just as the properties of atoms depend upon the configuration and orderly arrangement of protons and electrons, and just as the properties of molecules depend upon the configuration of the atoms, so the properties of life-units depend upon the orderly arrangement of molecules of various kinds into complex units of a higher order. That the orderly arrangement of parts is an essential feature of living things was recognized by the first person who called living things "organisms." What is the simplest life-unit? So far as we now know, the smallest unit of living material capable of existing independently and of maintaining itself is the unit called the *cell*.

The term "cell" was given to the life-unit by the first investigators who examined living tissues under the compound microscope. They saw in the tissues of plants small, boxlike compartments resembling prison cells. These compartments are merely the walls separating the living units and are not alive. Yet in spite of the subsequent recognition that the true units of life are the small masses of viscous material within the walls, the name "cell" has been retained and is now in universal use.

Whenever the tissues of the higher organisms, whether animals or plants, are examined under a good microscope they are found to be composed of cells.

In many-celled organisms (Metazoa and Metaphyta) cells may be looked upon as the structural and functional units out of which more elaborate and complex units (organisms) are constructed, much as rooms are the units out of which buildings of all degrees of complexity may be built. Cells, however, are rather more variable in form and in function than are rooms. They vary in size, shape, and position according to the rôle they play in the organism. In other words, their structure, like that of rooms, is more or less an index of their function (Fig. 23).

Thus, the largest cells in some organisms are eggs, which may attain a size of some inches in diameter. Eggs are reproductive cells produced by female individuals and are commonly gorged with food material (yolk) destined for embryos to be derived from them; large size is for them a prime necessity. Sperms, the male reproductive cells, are excessively small, but what they lack in size they make up for in numbers and in locomotor powers; for their first function is to reach the egg, a task of some difficulty and involving excessive travel for such tiny beings. A nerve cell is often prolonged into a tenuous process, an axon, that serves to connect tissues many inches apart. Such a form is necessary for a tissue that performs the rôle of an electric wire, i.e., transfers energy between somewhat distant points. Muscle cells are usually elongated; such a form is good for shortening or contraction, and muscles are primarily contractile in function. Most cells are

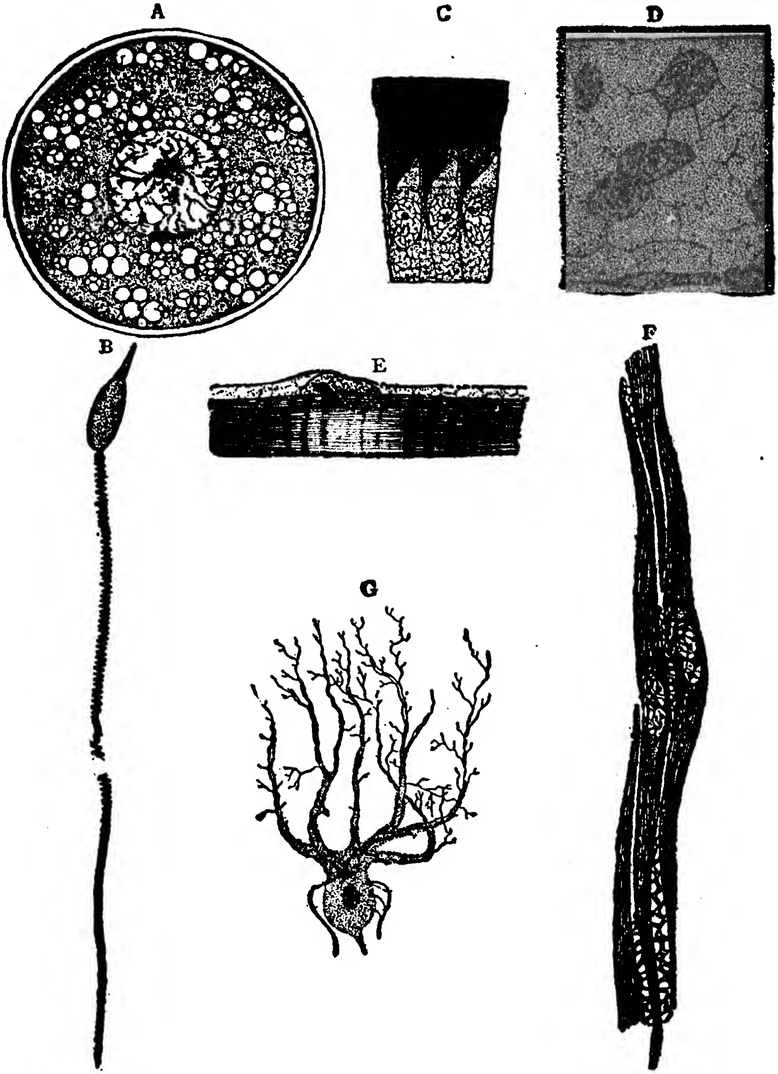


FIG. 23.—Various kinds of cells. *A*, female germ cell, ovum of a cat. *B*, male germ cell, spermatozoön of a snake, *Coluber*. *C*, ciliated epithelium from the digestive tract of a mollusk, *Cyclas*. *D*, cartilage of a squid. *E*, striated muscle fiber from an insect larva, *Corydalis cornutus*. *F*, smooth muscle fibers from the bladder of a calf. *G*, a nerve cell from the cerebellum of man. (From Hegner, after Dahlgren and Kepner.)

packed together side by side and are likely to be polygonal in form, but when cells are free, as in the case of many egg cells, they tend to round up into spherical form, for the sphere is the most compact geometrical form, since it has the least possible surface for a given volume.

THE ORGANIZATION OF A TYPICAL CELL

A cell was long ago defined simply as a mass of protoplasm containing a nucleus. While these two parts, nucleus and cytosome (as the non-nuclear protoplasm is now called), are usually considered the irreducible minimum of cellular organization, it must not be forgotten that some primitive plant cells have no differentiated nucleus and consist of an apparently homogeneous mass surrounded by a cell membrane. Such a cell then has two distinguishable elements in its organization, a differentiated surface membrane and a central mass of protoplasm. In higher plants the nucleus is added as a new differentiated region. All cells probably have at least two regions, cytosome and cell membrane.[1]

When one undertakes to describe the structures and functions of a typical cell and its parts, it becomes imperative that he decide upon some one class of cells as typical. Plant cells and animal cells are fundamentally different in some respects. The cells that constitute one-celled organisms also differ widely from the tissue cells of higher animals, and the various specialized types of tissue cells present a wide range of diversity among themselves. How then can one ever describe a typical cell? The best we can do under the circumstances is to present a diagrammatic figure that is a sort of composite of various kinds of cells, but like none in particular. Such a cell is shown in Figure 24, taken from the monumental work of Professor E. B. Wilson, one of the greatest living students of cells.

[1] Even such "naked" cells as *Amoeba* (until recently thought to have no cell membrane) have been shown to possess a well-defined surface pellicle which may be lifted off by the use of delicate glass needles from the underlying cortical protoplasm.

THE FUNCTIONING PARTS OF THE CELL

The nucleus.—The form of the nucleus is commonly spherical, but it may be elongated, branched, or discoidal. It always contains a peculiar type of protein material known as chromatin, believed to be the specialized vehicle which transmits hereditary differences.

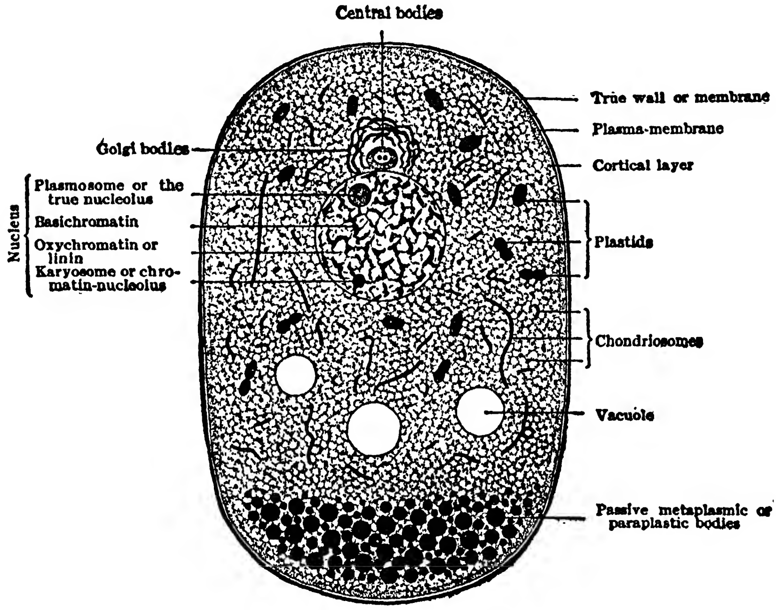


FIG. 24.—General diagram of a cell. Its cytoplasmic basis is shown as a granular meshwork or framework in which are suspended various differentiated granules, fabrillae and other formed components. (From E. B. Wilson.)

The cytosome of at least many cells is made up of a definitely organized system of structural components lying in a homogeneous ground substance that exhibits a polar gradation in respect to rates of metabolism. The formed substances of the cytosome consist of: (*a*) the central bodies (centrosomes) which seem to constitute the foci of the energies employed in cell division; (*b*) granules of various kinds; (*c*) plastids, or solid masses of materials

of various sorts; (*e*) chondriosomes, more or less complex cell organs whose function is not well understood; (*e*) vacuoles containing fluids; and (*f*) fibrils of many sorts. Some cells lack one, some another, of these listed organs of the cytosome (Fig. 24).

The cell membrane and the nuclear membrane are functional organs of great importance. Each serves as a barrier between materials of different constitutions. The cell membrane cuts off the living protoplasm from the harmful action of water and other surrounding media. At the same time it controls the intake and outgo of the cell, letting only waste products out and food products in. The nuclear membrane plays the same rôle for the nucleus, controlling exchanges between the different protoplasms of nucleus and cytosome.

Cytology, the special science of cell structure and function, recognizes a much more complex organization in most cells than we have described, but we have before us a general picture of the organized unit of life.

ONE-CELLED AND MANY-CELLED ORGANISMS

One-celled organisms.—A very large group of animals and an equally large group of plants consist of individuals composed of but one life-unit. These are called protozoa (unicellular animals), protophyta (unicellular plants), and bacteria, an immense group, sometimes called plants, but possibly a group co-ordinate with the protozoa and the protophyta.

Within the bounds of a single cell membrane and usually with but one nucleus,[1] the primitive animal or plant carries on all of the characteristic vital activities. Though these organisms are unicellular they are not necessarily simple, for in some protozoa the differentiation of special organs for different functions is amazingly complex.

Many-celled organisms.—In true multicellular organisms (Metazoa and Metaphyta) we have a new situation. The cell is

[1] Some specialized types of Protozoa have regularly two or more nuclei at all times, while others have a multinuclear phase during the complicated life-cycle.

no longer the real unit of organization, but is only a minor structural unit subservient to the organism as a whole. The organism controls the individual cells, determines that some shall specialize for one function, others for another. The cell then becomes but a minor substation for carrying on special kinds of energy traffic. We have stepped up to another threshold of natural units, a complex organism made up of minor units, cells, integrated and organized in perfectly definite ways into much greater and more complex units. We have a parallel to this situation in the cosmic systems and in the realm of physics and chemistry. A solar system is definitely organized in itself; yet it is but a minor part in a larger system, the galaxy. Similarly, the atom is an organized system in itself, but it may be only a minor part of a greater system, the molecule.

THE BASIS OF INDIVIDUALITY IN ORGANISMS

A glance at the diagram of a typical cell (Fig. 24) shows that the various components of such a cell are not thrown together at random, but are arranged in definite and precise fashion. An imaginary line drawn from the middle of the upper pole (the animal or apical end) to the lower pole (vegetal or basal region) constitutes a sort of axis about which the parts of the cell are grouped. The axis passes through the middle of the central body, bisects the nucleus, and has the other organs of the cell arranged symmetrically about it. It will be noted that the clear, more or less homogeneous protoplasm is aggregated mainly at the animal pole where the metabolic rate is highest, while most of the relatively inert solid or semisolid components are aggregated in the basal region. It has been experimentally proved for many cells that a quantitative gradient in metabolic rate runs from the apical to the basal pole, and that the various formed components of the cell are arranged in definite relation to this gradient.

This dynamic gradient that lies at the basis of individuality and organization in the cell is carried over into the multicellular

organism when the single egg cell repeatedly divides to form the multicellular adult. Whether in the single cell or in the complex organism the basis of individuality is the same. Unity of organization is the result of the important fact that the most active region dominates the whole system. Hence a cell or a more complex organism is a unit because all parts are subservient to one centralized authority, just as a great business organization acts as a unit because dominated by one chief executive.

HOW CONTINUITY OF ORGANIZATION IS MAINTAINED

CELL DIVISION

Having developed the idea that a cell is an organism with a very exact configuration of its parts, the question naturally arises as to how cells originate. Older biologists thought that cells arose much after the manner of crystals, by a process called "free cell formation," but no one ever saw a cell originate in that way. Since 1855 it has been the universal conviction of biologists that all cells arise through the division of previous cells, back to the primitive ancestral cell. Cell division is the essential mechanism of reproduction, that of heredity, and to a large extent that of organic evolution. No more fundamental biologic process could well be studied. If we entirely understood the mechanism of cell division we should be far on our way toward an understanding of the "mystery of life."

There are usually described two methods of cell division, one a relatively simple, rough-and-ready method known as *amitosis*, and the other the indirect and complicated method of *mitosis*. We shall confine our attention to the latter, for there is some question as to the actual rôle of amitosis and, at best, its significance is little understood.

The events of mitosis.—The process of mitosis is found in both animals and plants, in both unicellular and multicellular animals. It differs in detail in different organisms, but however varied in details the process may be, it is basically the same wherever

found. The process here described is that typical for the cells of higher animals, but is not meant to be exactly like that of any particular species. The series of orderly events about to be described constitutes one of the marvels of biology. The various changes are as nicely adjusted and as precise as are the movements of planets in the solar system or of electrons in the atom. As to the dimensions of the systems involved, one would not be far wrong if he placed them midway between that of the solar system and that of atoms. To the atom a cell is a vast universe; to a solar system a cell is a tiny atom. If we have gained the proper perspective we shall realize that a dividing cell may be the scene of vastly complicated maneuvers of extraordinarily large and complex molecules, of cosmic processes as majestic as those of the stars in the galaxy.

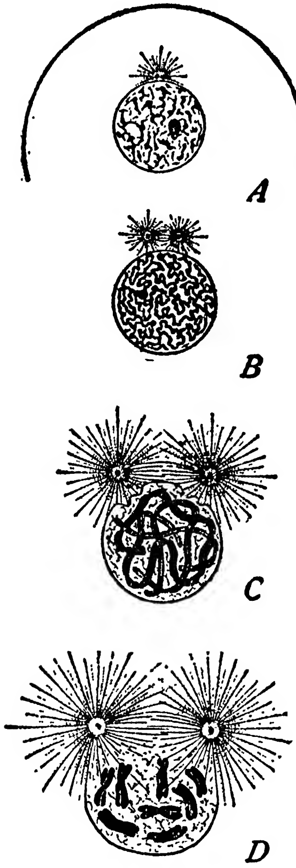


FIG. 25.—Diagram of the prophases of mitosis in *Ascaris*. *A*, vegetative nucleus; *B*, fine spireme; *C*, coarse spireme; *D*, late prophase with chromosomes, spindles forming. (From E. B. Wilson.)

Mitosis is observed in embryonic, or developing, cells. When a cell divides into two daughter cells, the latter are only half the size of the parent cell, and they at once begin to grow. When they reach the maximum size, they in turn divide. There is thus a rhythm between periods of growth and periods of division. Without going into any technical details, let us give a simple running account of a single mitotic division.

When a cell is full grown and ready to divide, the central body takes the initiative (Fig. 25, *A*). The single minute centrosome divides into twin centrosomes that migrate apart and organize between them a characteristic spindle-shaped bundle of fibrils, known as the mitotic spindle (Fig. 25, C). Commonly each centrosome has about it a halo of radiations, believed to be indications of energy emanating from it. While these changes have been going on in the cytosome, equally striking changes have been taking place in the nucleus (Fig. 25, *C* and *D*). The chromatin, originally in a finely divided state, has condensed first into long threads, then into definite pieces known as chromosomes.[1]

Let us now bring together and consider as one process the two processes just described separately. The central bodies and the chromosomes co-operate to form the so-called mitotic figure (Fig. 26, *E*), consisting of a spindle composed of fibers, two asters at the poles of the spindle, and the chromosomes. The chromosomes move slowly toward the middle of the spindle and come to rest in an exactly equatorial position, equidistant from the two poles.[2]

[1] The form taken by the condensing chromatin is as characteristic and specific as is the crystalline form of a chemical compound. Not only are the shapes and sizes of the chromosomes characteristic, but the number of chromosomes, except under peculiar circumstances that we need not consider here, is quite constant for a given species. For example, a certain species of crayfish has 200 chromosomes, one species of water flea has 168, a species of moth has 62, man has 48, a species of salamander has 28, the pine tree has 24, maize has 20, Lamarck's evening primrose has 14, Drosophila (the classic fruit fly) has 8, one variety of the maw-worm of the horse has 2. Why the even numbers? This is most significant, but the reader must wait for its explanation until he reads chapter xiii. It may readily be inferred from the list of chromosome numbers given that numbers of chromosomes do not parallel degrees of specialization, for some of the simpler organisms have the highest numbers.

[2] When the chromosomes lie in equilibrium between the two poles, we have a picture of balanced forces that is much like that produced when iron filings scattered on a sheet of paper are brought under the influence of the opposite poles of a horseshoe magnet. The two pictures are much the same, but an essential difference lies in the fact that, whereas the two poles of the magnet are of opposite sign, those of the mitotic figure are of the same sign. If the physicist could explain the mitotic figure in terms of known laws he would do a great service to biology, for this is one of its most baffling problems.

When the chromosomes lie in equilibrium between the two poles they are split lengthwise into daughter chromosomes, each half chromosome having an equal share of everything present in the parent chromosome (Fig. 26, *E*).

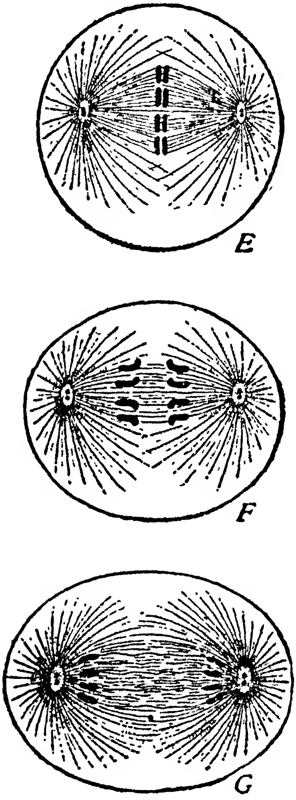


FIG. 26.—Diagram of the middle phases of mitosis. *E*, metaphase; *F*, *G*, earlier and later anaphases. (From Wilson.)

Then ensues a period of separation of half-chromosomes and their migration, or transfer, toward the opposite poles of the spindle (Fig. 26, *F*, *G*). Thus two groups of chromosomes precisely alike, and also like the parent group, are collected at opposite sides of the cell (Fig. 27, *H*).

Now comes the last act of the drama. The cell membrane pinches in along the plane of the equator of the spindle, cuts the cytosome into two equal (or sometimes unequal) parts, the chromosomes go through the reverse process of becoming more diffuse, a new nuclear membrane is formed, and a primary act of reproduction has been completed, in that from one cell two have been produced (Fig. 27, *I*).

It is especially important to notice how beautifully the mechanism subdivides the chromosomes and other important cell organs, so that each daughter cell will have the same detailed organization possessed by the parent cell. This is the reason why offspring resemble parents and why there is a certain degree of organic stability that enables us to distinguish races, species, varieties. If the mitotic mechanism were the only machine involved in reproduction, and it never slipped a cog, we should find no change from generation to

generation and species would be immutable. But there is a variation machine just as well adapted for producing new situations as is the mitotic mechanism for maintaining old standards, and hence the living world does not have a chance to stand still. Also there is going on a slow but constant change in the chromatin material itself. The mechanism of variation is to be discussed in chapter xiii.

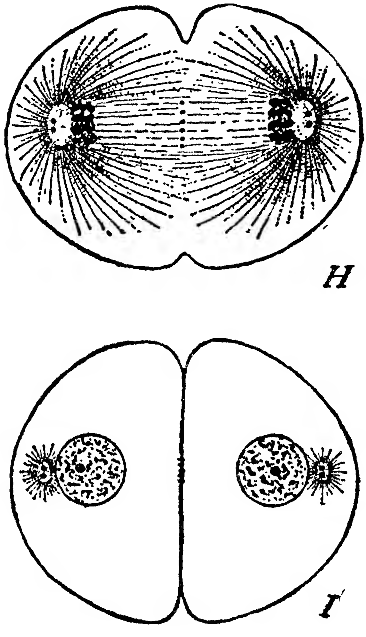


Fig. 27.—Diagram of closing phases of mitosis. *H*, the beginning of constriction of the cell membrane; *I*, the completed division. (From Wilson.)

DEVELOPMENT

If an organism consists of but a single cell, a division of that cell results in two organisms and that is the end of it, except that each daughter cell will need to grow and to differentiate some new parts. But in many-celled organisms, when the egg cell divides into two daughter cells, these do not part company to become separate organisms. Instead, they remain together as parts of a single organism. Each cell divides again and again, passing through four-cell, eight-cell, sixteen-cell stages, and up to hundreds of cells. This period of cell multiplication (technically known as cleavage) takes place rapidly and without much time for growth between divisions. The cells become progressively smaller in size until at the end of the cleavage period there is formed a hollow ball of cells (the blastula) in which, typically, all cells are in contact with the surface. Various modified blastulae exist among specialized organisms. Thus the blastula may consist of a solid ball of cells, a hollow ball with walls several

cell layers thick, or a large non-cellular mass of yolk with a thin sheet of cells at the animal pole, as in birds and reptiles.

Usually as an accompaniment of cell multiplication cell differentiation occurs. Some cells are cut off on the surface, while others are crowded from the surface; some are formed from materials near the animal pole, others from near the vegetal pole. These and other differences, physiological or mechanical, bring about a sort of division of labor among cells. While this is going on the multicellular mass remains an organism with an axis of polarity and usually one of symmetry. At no stage of development is there any tendency for one part to act as though independent of the others. All parts remain in subordination to the apical end.

After the blastula is formed, the next great step in development is known as gastrulation. Typically, the cells of the vegetal pole are pushed in so as largely to obliterate the hollow of the blastula, and a second hollow is formed (the archenteron), or primitive gut. A gastrula is now formed, possessing a layer of protective, locomotor, and sensory cells (ectoderm) on the outside, and a layer of digestive cells on the inside (endoderm), communicating with the exterior by an opening, the blastopore. Nearly all multicellular animals have recognizable gastrula stages, though it takes an expert to interpret some of the much distorted conditions seen in specialized forms.

In most multicellular animals, in addition to the two primary germ layers, ectoderm and endoderm, a third germ layer (mesoderm) develops, sometimes in one way and sometimes in another. The mode of mesoderm formation constitutes one of the broad general dividing lines among animals. After the mesoderm is formed, other organs differentiate out of the three primary germ layers. The ectoderm goes to form the organs of the skin, including sense organs, ciliated cells for locomotion, protective cells, and nerve cells. The endoderm forms the lining of the digestive tract and of its derivatives, such as lungs, liver, and various other glands. The mesoderm forms bones, muscles, blood, and blood

vessels, and many of the bulkiest of the body tissues. All this increasing complexity is the result of cell division accompanied by cell differentiation. In a subsequent chapter a description of the development of vertebrates, and especially of man, will serve to give a more concrete picture of the developmental process. The present preliminary sketch is introduced in order to emphasize the facts that development is essentially a cellular phenomenon, a direct result of mitotic cell division, and that it is always controlled and guided by the axiate organization.

II. THE ORIGIN AND EVOLUTION OF LIFE

The problem of the origin of life is a double one, each part of which demands separate consideration. The first inquiry has to do with the origin of new life today; the second, with the first origin of life on the earth or elsewhere.

THE ORIGIN OF NEW LIFE TODAY

In our discussion of cell division and reproduction we have already stated that every new organism arises from a previous organism through the separation of a cell or a group of cells from a parent. This is a statement of the principle of biogenesis, that new life today originates only from previous life—*omne vivum ex vivo.* Although science is practically unanimous for biogenesis, the layman very generally assumes the contrary and is ready to believe in abiogenesis (spontaneous generation). Who has not at some time been told that a horsehair, if left in a watering trough, will change into a long black worm? Who has not encountered the belief that mold is generated in canned fruit or develops out of the substance of cheese? Who has not been assured by eyewitnesses that tadpoles come down in rain?

The early Greek and Roman natural philosophers and poets agreed that new life is constantly arising spontaneously or through supernatural intervention. Even as late as the sixteenth century Van Helmont, a famous physicist and chemist, concocted a recipe for engendering scorpions. He said:

> Scoop out a hole in a brick, put into it some sweet basil, crushed. Lay a second brick upon the first so that the hole may be perfectly covered. Expose the two bricks to the sun, and at the end of a few days, the smell of the sweet basil, acting as a ferment, will change the earth into real scorpions.

This type of belief was common to all until late in the sixteenth century when Redi disproved the current doctrine that maggots were engendered from the juices of decaying meat. He simply put a screen over a vessel of meat, thus excluding the flies, and found that no maggots appeared on the meat. The eggs of the flies, however, that were laid on the screen hatched out into maggots. Although the experiments of Redi discredited belief in the spontaneous generation of larger organisms, the idea that bacteria and other microscopic organisms developed *de novo* in nutritive media persisted until the middle of the nineteenth century when Louis Pasteur showed its untenability. By simple processes of sterilizing nutritive media by heat and preventing the ingress of spores he proved that, unless bacteria are introduced, nutritive media remain permanently free from them, and that no organisms arise spontaneously in them. The work of Pasteur has been amply confirmed by many other experimenters with the result that today it may be said that there is no scientific evidence for spontaneous generation and much against it. Yet it would be dogmatic to deny that any of the very lowest expressions of life, such as the filtrable viruses or even simpler molecular complexes just beyond the borders of protoplasmic organization, may be arising *de novo* today. So eminent an authority as T. C. Chamberlin holds that life may be making new starts even today, but that the available materials for the maintenance of such compounds are everywhere pre-empted by the ever-present forms of life already in existence. Hence new life substances are robbed of their opportunity to realize their developmental possibilities. It is unsafe, then, to conclude that life cannot, under favorable conditions, arise by natural processes of synthesis even today. All we can be sure of is that no such origin has yet been observed in nature nor induced in the laboratory.

The fact that man has not succeeded in making a new living organism nor observed the spontaneous generation of life in nature, does not drive us to a supernatural origin of life. We are frank to admit that as yet we do not know just how, when, and where life began on the earth, but we are not yet ready to abandon hope of the ultimate scientific solution of the problem.

Theories of the beginnings of life on the earth.—Man has not been satisfied to relegate this difficult problem to scientists of the future. On the contrary, many earnest and serious efforts have been made to solve it. Such names as Richter, Helmholz, Kelvin, Pflüger, Troland, Chamberlin, Moore, Allen, Osborne, have been associated with this adventure into uncharted fields of scientific inquiry. While some of the theories are interesting, logically sound, and at least suggestive, it seems hardly appropriate to introduce here material so highly speculative. In all frankness it must be admitted that the problem of the origin of life has not been solved. At best we have nothing more than a series of preliminary hypotheses (see pp. 52–53).[1]

In making these admissions we realize that we are offering a vulnerable point of attack to the obscurantist. He has a simple and naïve solution of this difficult problem. Such an explanation is entirely satisfactory to some minds, but quite inadequate for others. We are not concerned with such matters.

THE EVOLUTION OF LIFE

The evolutionist frankly admits that he knows nothing about how life began and therefore confines his interest to changes in life after it once appeared. The astronomer and the geologist have dealt with the evolution of universes and solar systems and have described the orderly and rhythmic changes of the earth's surface. The physicist and the chemist have shown that there has been an evolution of elements and all sorts of transformations of matter. If the relatively fixed and stable materials composing the moun-

[1] A good account of these theories is given by L. L. Woodruff in *The Evolution of the Earth and Its Inhabitants*, 1923. See No. 4 of "Selected References" at end of this chapter.

tains, the rocks, the elements, are continually changing; if there have been vast fluctuations in climate and in the general environment during the period that life has existed on the earth; if the whole non-living universe is ever changing, it is hardly conceivable that the highly unstable living materials that are constantly building up and breaking down, and constantly adjusting themselves to changed environments, should remain fixed. If life were able to remain immutable in an ever-changing universe we should have a tremendously difficult problem to account for its fixity. Orderly change would seem much more natural.

The theory of evolution holds that, once life got started, it began to change at once in adaptation to diversified conditions in the environment; that, in general, the changes have proceeded from more plastic, generalized types to less plastic, specialized types; that immense numbers of highly developed types have appeared, have thrived for a time, and then have died off; and that the forms living today are merely the present end-products of thousand of lines of specialization, each descended from the simplest form of life.

The antiquity of the evolution idea.—Contrary to popular belief, the idea of evolution is a very old one. Certainly it dates back as far as the early Greeks and doubtless was held by the still earlier Egyptians. Among the Greeks the leading proponent of the evolution theory was Aristotle, who as early as the fourth century B.C. had already developed a comprehensive theory of evolution, resembling in principle the modern conception, but differing in many details. Although minor additions were made from time to time during the next two thousand years, it was not until the nineteenth century that the next great advance was made by Charles Darwin.[1] Darwin's permanent contribution to the subject was made possible through the use of the scientific method: that of first amassing an adequate array of facts and then developing a theory to explain and rationalize them. Darwin had a pas-

[1] The idea of slow orderly change was current in astronomy and geology long before it became generally accepted in biology.

sion, even a reverence, for facts. When his preliminary survey of facts suggested an evolutionary interpretation he was not yet ready to proclaim his conclusions to the world. Instead, he spent twenty more years gathering additional facts and testing the bearing of each on the evolution hypothesis. In 1859 he published his classic work, *The Origin of Species*, a book probably more influential in shaping the thought of humanity than any other scientific book ever written. The truth of evolution was so plainly demonstrated by Darwin that it was accepted widely by scientists even as early as 1865, and since then it has gained general acceptance among scientists.

It would be far from the truth to say that the principle of evolution has been universally accepted. For that matter it is not universally believed that the earth is spherical, rotates on its axis, and revolves in an orbit about the sun. The reason for popular skepticism of scientific explanations is that frequently they seem to run counter to human experience. Thus the earth looks flat and the sun seems to revolve about it. Similarly, the species of animals and plants seem to be immutable, for to the casual ob server they appear to remain the same generation after generation. One cannot readily observe the transformation of species and it is therefore difficult to believe that such processes have taken place in the past. It is not a simple matter to prove the validity of the principle of evolution, but the proof, once studied and understood, is so cogent that no biologist today doubts that the principle is valid.

IS EVOLUTION PROVED?

Scientifically, evolution is a law of nature and is proved or established as firmly as is the law of gravitation, and precisely in the same way. Just as the theory of gravitation was an inference derived from facts and has served to explain and rationalize other facts, so the theory of evolution was offered as an explanation of facts and has served to make intelligible enormous numbers of facts quite obscure on any other grounds. Thus classification, comparative anatomy, embryology, palaeontology, and geographic dis-

tribution become consistent and orderly sciences when viewed from an evolutionary point of view, but when viewed from any other point of view they are left in the utmost confusion. There is no other explanation known to man that is of the least value in giving these bodies of fact any sort of scientific coherence and unity. In other words, the working hypothesis of organic evolution does everything that any good hypothesis could be asked to do: it works, and as long as it continues to explain and to agree with new facts and to meet all the tests to which it is put, it must be considered as valid. Not only does the hypothesis work, but, with the steady accumulation of further facts, the weight of evidence is now so great that it overwhelms all intelligent opposition by its sheer mass. There are no rival hypotheses in the field except the outworn and completely discredited doctrine of special creation. If, however, any fact or body of facts entirely irreconcilable with the theory of evolution were to be discovered, the theory would have to be abandoned, or at least so modified as to fall into agreement with the new facts. What a sensation would be created in the world of science if anyone could today bring to light some definite evidence to confute the evolution theory! A man could become famous the world over, and that immediately, if he succeeded in disproving or even in seriously weakening the principle of evolution. The opponents of evolution might well join the ranks of scientific investigators and help to bring to light these so far elusive facts whose discovery would overthrow the theory of evolution. At present there are no known facts contrary to evolution and scores of thousands of facts that accord with it. Could any scientific principle be better established than this? From the standpoint of science then we may conclude that evolution is proved.

Not only is the general principle established that organisms have evolved and that the species of today are descended from different species in the past, but we know in detail much about the actual course that evolution has taken. We are able to follow the main trends in such large groups as the vertebrates; in some

cases we can even trace step by step the ancestral history of modern forms.

THE METHODS OF THE EVOLUTIONIST

One of the chief tasks of the biologist is the working out of pedigrees of the species living today. Various specialists, each working out the details in one small section of the field, contribute results that may be put together into one great general compendium of animal and plant ancestries. A favorite method of expressing the boiled-down findings of those whose task it has been to search out pedigrees is to construct a phylogenetic, or ancestral, tree such as that shown on page 263. But, you may well ask, How does one go about the task of reading the ancestral history of a species? It is by no means a simple matter to get the data for a pedigree. Information comes from all sorts of different sources, some of them often quite unexpected. In the main, however, the searcher after ancestors has a well-developed method of attack.

The method of comparative anatomy.—If a biologist wishes to discover the ancestry of a particular species, he studies numerous other animals more or less like the one concerned in the hope of finding some traces of characters among these that suggest the ancestral condition of these species. There are always some members of any group that are more conservative than others in one or more respects, and, therefore, more nearly ancestral. If one summarizes the most primitive features collected from all the members of the group and ascribes them to a common ancestor of the group, he then has something that he can use as a working hypothesis—a hypothetical synthetic ancestor. The validity of such a procedure may then be tested by other methods.

The method of embryology.—The development of the embryo of the species or group in question is then studied. Invariably, during the course of development, the embryo passes through conditions strikingly like those of more primitive types of organisms. As a rule, the earlier stages of development reveal characters not persistent in the adult, but possessed by the hypothetical ancestor synthesized by the comparative anatomist. If

one confines his attention to one organ or one system at a time, he can see such an organ or system originate in a condition closely resembling equivalent structures of the lowest organisms; he can see this structure pass through stages like those in somewhat higher organisms, and finally emerge in the definitive form. The developmental history of an organ or a system is, then, often like a moving picture of the evolution of that structure, but is often extremely abbreviated, censored by time and the changing environment. When considered along with comparative anatomy, however, the method of embryology gives immensely valuable data about ancestries.

The method of paleontology.—It is one of the most fruitful. This method consists of a search for the preserved remains (fossils) of extinct animals and plants. Naturally enough, we find among these very numerous preserved parts of prehistoric organisms many that are just what one, on the basis of comparative anatomy and embryology, would expect the ancestors of modern forms to be like. Very often fossil forms have been found that have the combined characters of two groups now quite unlike. Such forms may with some confidence be interpreted as connecting links or common ancestors of these divergent groups. In many instances long series of gradually changing forms have been found preserved as fossils, and their sequence in the layers of rock are just what one would expect them to be if they represent an ancestral series. Thus paleontology goes a long way toward confirming the findings of comparative anatomy and embryology.

The method of blood tests.—This is the newest of phylogenetic methods. It has been discovered that the chemical make-up of the blood serum of organisms is a good index of their degree of relationship. Those known to be most closely related show the closest resemblances in blood composition. The method of determining resemblances and differences in blood composition is somewhat complicated, but enables the investigator to gauge the degrees of blood resemblance, and hence relationship, with some

degree of accuracy. The most important feature of the blood-test method, however, is the fact that it strongly confirms phylogenetic relationships established through the methods of comparative anatomy, embryology, and palaeontology. It is certain that a failure of this new method to confirm the findings of older methods would greatly have weakened our confidence in these findings. When, however, the new method so strongly corroborates the old, our confidence in the validity of both old and new is correspondingly strengthened.

Other methods more difficult to describe are used in order to gain additional information about ancestries. Lack of space forbids more than the mere mention of the methods of geographic distribution, genetics, comparative physiology, and studies of behavior.

The following six chapters may be looked upon as a statement of the facts that have been discovered about organic evolution. In most instances the writers give the present status of expert opinion regarding the various aspects of evolutionary history. The statements are based upon information derived from the sources just indicated. They do not pretend to be final, but represent the well-considered conclusions of experts. New information is coming in so rapidly that every year sheds some new light upon obscure places. The plan of the series of evolutionary chapters is one that involves a succession of forms of life beginning with the bacteria and leading up to modern man. The chief emphasis is upon man, for man is the most important organism we have to deal with in the world of today.

SELECTED REFERENCES

1. H. H. Newman, *Outlines of General Zoölogy* (The Macmillan Co., 1925), chaps. i–ix.

2. H. H. Newman, *The Gist of Evolution* (The Macmillan Co., 1926)

3. E. B. Wilson, *The Cell in Development and Heredity* (The Macmillan Co., 1925), chaps. i and ii.

4. L. L. Woodruff, "The Origin of Life" (chap. ii) in *The Evolution of the Earth and Its Inhabitants* (Yale University Press, 1923).

CHAPTER VII

THE BACTERIA

EDWIN O. JORDAN

The nature of bacteria.—Bacteria are among the smallest living organisms. It is difficult to get a conception of their extreme littleness. The typhoid germ, which is shaped like a lead pencil stub, is a bacterium of about average size. It is so small that laid end to end it would take about 12,000 to form a line 1 inch long. A cubic inch would hold about 9,000,000,000,000 typhoid bacteria. It is not surprising that the earlier microscopists loved to talk of "the world of the infinitely little."

The exceeding minuteness of bacteria has made it necessary to use special methods for studying them. Individual bacteria can be seen only with the microscope and even then only with the highest magnifications. If we could view a man under one of our most powerful lenses he would appear somewhat taller than Pike's Peak, but under the same power some of the smallest bacteria appear about the size of the periods and commas of good print. To distinguish the different kinds of bacteria one from another we must grow them in great numbers, observe them in masses, and study their effects on their surroundings. It is as if we had to distinguish oaks from maples by viewing them in groves from a balloon at a great distance.

It is not certain that bacteria are really the smallest of all living things. There is some reason to believe that still smaller organisms exist. Our best microscopes do not enable us to see distinctly objects that are less than 1/250,000 of an inch in diameter. The germs of certain diseases, as for instance those of vaccinia virus and the foot-and-mouth disease of cattle, are so minute that they will pass through the fine pores of a filter made of baked clay or infusorial earth. There are other filtrable viruses which

cannot be seen but which are self-propagating and behave in many ways like living organisms. Whether some or all of the filtrable viruses are microbes that should be classed as bacteria is not known at the present time. Some investigators believe that bacteria themselves are subject to attack by parasites too small to be seen, but about this there is much dispute.

The visible bacteria can be readily photographed (Fig. 28) and many of them can be grown in masses or "colonies" on nutrient substances such as beef jelly, where they can be seen with the naked eye (Fig. 29). There are three chief forms: the sphere (coccus, streptococcus), the rod (bacillus), and the spiral or corkscrew form (spirillum, vibrio) (Fig. 30). In a fluid medium many but not all bacteria are able to swim about freely with a brisk but not exceedingly rapid motion. Measured by their own length the rate of speed of bacteria is more like that of a riding horse than of an automobile.

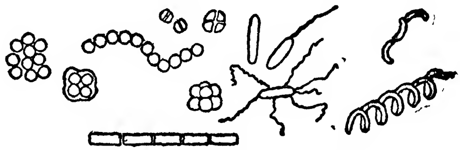


FIG. 30.—Forms of bacteria

Bacteria are more resistant to injurious influences than any other organisms known. Some of them when in the spore stage can withstand drying for months and years. They have great resistance to cold and heat. Most forms of bacteria are killed like other living things by a brief exposure to temperatures of 60°–65° C., but certain spores may not be killed even by exposure to boiling water for as long as 16 hours. The wide range of temperatures at which bacteria can live and multiply is especially noteworthy. Certain kinds have been found living in the water of hot springs at a temperature of 89° C., while others are able to multiply at or near the freezing-point. Bacteria in the ordinary vegetative stage are killed by the usual protoplasmic poisons, but powerful chemicals—germicides—must be carefully applied under suitable conditions in order to insure the destruction of spores.

In view of their great adaptability and high power of resist-

ance it is not surprising that bacteria are well nigh ubiquitous. They cling to dust particles and are blown about by the wind and so find their way into remotest crevices. Wherever favorable conditions of food, moisture, and temperature exist multiplication soon begins. We accordingly find bacteria in the tropics and at the poles, in soil, water, and organic substances of various kinds, in the bodies of living animals and plants, on mountain-tops, and in deep sunless mines. No other group of living organisms is so widely distributed.

One of the most characteristic and amazing things about bacteria is their rapid multiplication. A rod-shaped bacterium, for example, elongates slightly and divides in two, and each half becomes at once an independent organism. In a short time—15 minutes under favorable conditions—each of these daughter bacteria is again capable of dividing, and this process may go on for several days. A simple calculation with paper and pencil will show that enormous numbers of bacteria may spring from a single parent individual. Supposing that division occurred only as often as once an hour, the descendants of one bacterium would in two days number 281,500,000,000 and in three days the weight of the progeny would amount to about 7,000 tons. Of course, under ordinary natural conditions multiplication does not proceed unchecked at such a rate. The food may give out, or the conditions of moisture and temperature may not remain favorable, or other micro-organisms may prey upon them, or they may be choked by the products of their own growth. The fact, however, that for a time bacteria may increase with astonishing rapidity helps to make plain why the effects produced by bacteria in a brief period are seemingly out of all proportion to the original exciting cause. A little leaven leaveneth the whole lump.

Are bacteria animals or plants?—It would be easier to answer the question whether bacteria are animals or plants were biologists agreed among themselves as to what the distinguishing characteristics of animals and plants really are. There is little difficulty in distinguishing the higher animals from the higher plants, a

man from a tree, a rose from a kitten. But the simpler organisms, especially the microscopic forms, are not so far apart. In general, free motion characterizes an animal, while a plant is fixed to its place in the soil or on a rock or is carried helplessly about by wind and wave. But many of the lower forms of aquatic plant life are able in certain stages of their development to swim about through the water, and conversely, some animals do not, at least in adult life, possess the power of locomotion. Moreover, some bacteria are motile while others closely related are non-motile. As an absolutely distinguishing mark therefore motility breaks down.

In their ways of getting food and in their general physiological characters bacteria are closely related to the fungi, especially the molds and yeasts. Structurally they are very much like some of the blue-green algae. On the other hand, they display certain resemblances to the simplest forms of animal life, the one-celled protozoa. The spirochetes, spirally-twisted organisms such as the germs of relapsing fever and some other diseases, are classed as bacteria by some biologists, as protozoa by others.

To escape from the difficulty of placing bacteria unreservedly in either the plant or the animal kingdom, the establishment of a third kingdom, the "protista," has been suggested. The protista would include those organisms of doubtful affinities which seem to have some plant characteristics and some animal characteristics. While at first sight such an arrangement might seem to solve our difficulties, as a matter of fact it would increase them, since instead of one boundary we should have two, and, in the case of certain organisms, we should have to decide whether to place them with the protista or with the animals; in the case of others, whether with the protista or with the plants.

On the whole and in view of the undoubtedly close structural relation of bacteria to certain blue-green algae, bacteriologists are inclined to group them with the plants rather than the animals. After all, the exact position in classification is not so important once we recognize the highly interesting and significant mixture

of characteristics which bacteria possess. They furnish one more piece of evidence testifying to the essential identity of living matter whether animal or plant. The earliest living things were, perhaps, strictly speaking, neither plant nor animal.

The origin of bacteria.—Many of the early microscopists were long in doubt as to the origin of bacteria. The minuteness, the great resistance to destructive influences, and the rapid multiplication of these organisms gave rise to peculiar and puzzling events. Bacteria would suddenly appear in great numbers where seemingly they had not been before; organic fluids heated to very high temperatures, indeed boiled for hours, would, after keeping fresh for weeks, finally break down through bacterial activity. By some observers these phenomena were explained as due to the spontaneous generation of bacteria out of organic matter. More skillful experiments, however, showed that the apparently spontaneous development of bacteria in these instances was due either to the entrance of bacteria from outside through small unseen cracks, or to the survival and subsequent generation of bacterial spores even after being heated to temperatures that would surely destroy all higher forms of life. In no instance has it been shown by unimpeachable evidence that bacteria ever originate except from other bacteria in the manner described above.

The relatively simple structure of bacteria, together with their ability to satisfy their food requirements from inorganic substances, have raised the question whether bacteria or organisms resembling them may not have been the first living things to appear on earth. A cogent argument for regarding bacteria as one of the earliest, perhaps the earliest, of living organisms is their ability to build up their body substance out of simple inorganic material. The chlorophyll and similar pigments which enable the green plants to effect this synthesis are lacking in bacteria. Since the higher fungi, such as mushrooms, are obliged to obtain their food from already developed organic matter, it may well be that those forms of bacteria which extract nitrogen from the air or are satisfied with solutions of simple mineral salts are but little

removed from the earliest forms of life. It is possible that bacteria —or some of them—may be the degenerated descendants of higher forms of plant life, but this does not appear so probable as that bacteria represent a very primitive type of living thing. How then did bacteria originate? One opinion that has been advanced is that bacteria or their progenitors were brought to the earth through space from some other planet, such a transfer being favored by the high power of bacterial resistance. This explanation merely removes the problem of bacterial origin to another planet where we can hope to know even less about the primordial conditions than we do about those on this earth, and is surely no explanation at all. We may as well face squarely the question as to the origin of life.

While there is little or no cause to believe that spontaneous generation is occurring at the present day, it is reasonable to suppose that some form of microscopic life developed out of inorganic matter at some previous period in the world's history. The continuity of development which is so striking a feature of the life-record found in fossil rocks may thus be seen to extend back to include the orderly and progressive development of the organic out of the inorganic. It is a remarkable possibility to contemplate—but no more remarkable than the known facts about the marvelous growth of crystals and the still more wonderful transmutation of one element into another, radium into helium, thorium into lead. We naturally have no direct evidence about the origin of bacteria on the earth, but it is quite in line with all of our other knowledge of life development to suppose that at some time in some way some form of microscopic life developed out of highly organized, but up to that time inorganic, matter.

The effects produced by bacteria.—The ability of bacteria to satisfy their need for food at the expense of a great variety of substances not only allows them to spread widely through nature, but also brings it about that bacteria produce rapid and profound changes in their surroundings. Individually small and seemingly insignificant, their multiplication is so rapid and their demand for

food so urgent that few other living things are able to accomplish so great a modification of their environment. It was once supposed that the oxygen of the air was by itself responsible for decomposition and decay, phenomena which are primarily oxidation changes, but it is now known that these processes could not go on without bacterial agency. Most bacteria get their food, their energy, chiefly from the complex organic compounds originally constituting the bodies of the higher plants and animals. When a plant or animal dies, the resistant forces of the living organism, which perhaps have long successfully withstood destructive bacterial invasion, disappear, and bacteria take energy from the complex organic molecules and build up their own body substances. In the breaking down of the organic matter a great variety of chemical changes is produced: gases such as ammonia, marsh-gas, carbon dioxide are evolved; solid bodies such as gelatin may be liquefied; fluids like milk may become a solid curd. When bacterial decompositions go on in the absence of the oxygen of the air, ill-smelling gases such as sulphuretted hydrogen may be given off. These chemical changes are often accompanied, like certain other chemical reactions, by a rise in temperature. The heating of manure and the spontaneous combustion of damp hay are at least in part due to bacterial activity. Light-producing bacteria are quite numerous, the phosphorescence of meat and fish being commonly due to these organisms. Certain photogenic bacteria have been photographed by their own light. Many kinds of bacteria produce pigments, orange, blue, yellow, or purple. It is not known in what way, if at all, the pigments and the luminescence of bacteria are of benefit to the organisms producing them.

Such familiar changes as the souring of milk, the conversion of cider into vinegar, the putrefaction of meat, and the spoiling of canned vegetables are caused by the endeavor of bacteria to satisfy their need for food. The very crust of the earth may be affected by bacterial action. There is some reason to believe that certain bacteria which have the property of precipitating iron oxide out of solutions of iron salts influence the formation of bog

iron, and so cause the accumulation of iron in such concentration that it can be profitably mined. Still other bacteria attack sulphur compounds. In certain of the "sulphur bacteria" granules of elementary sulphur appear in the bacterial cell from the oxidation of hydrogen sulphide.

From the standpoint of man, bacteria may be viewed both as friends and as foes. Certain kinds invade the body of man and other animals and produce serious disease. Other kinds are distinctly beneficial in the effects they produce.

Bacteria as friends.—The importance of bacteria in the economy of nature can hardly be overestimated. That nitrogen is essential to all living things is well known. The complex nitrogen compounds that constitute a vital part of all protoplasm are being continually broken down by metabolic activity—the basis of life itself—and cast out of the cell. They are then oxidized by the bacterial action to the mineral form of nitrate or restored to the great atmospheric storehouse of free nitrogen. Through the aid of sunlight the green plants are able to build up out of nitrates organic nitrogenous substances. In this way the circulation of nitrogen is maintained. But for bacteria the nitrogen cycle would be interrupted at a critical point, and much of the earth's nitrogen would be sealed up in the lifeless bodies of plants and animals. Picture the earth's surface cumbered with the dead bodies of plants and animals unaltered by decay!

Agricultural processes vitally essential to man are dependent on bacterial action. Not only are the organic and mineral matters in the soil being constantly worked over by the bacteria even more fundamentally than by the earthworm, but certain bacteria are continually enriching the soil by taking nitrogen from the inexhaustible reservoir of the air and "fixing" it in the soil.

The fact that a soil is improved by allowing it to lie fallow has long been known to practical farmers The nitrogen-fixing activity of the soil is largely due to bacteria. It is also well known that certain crops, such as clover, increase the nitrogen in the soil. This is due to a singular association of bacteria with these higher

plants. Colonies of bacteria occur in the roots of clover and other leguminous plants, forming "nodules" plainly visible to the naked eye (Fig. 31). These nodule bacteria in co-operation with the clover plant utilize the free nitrogen of the air so that plowing under a crop of clover increases the store of soil nitrogen. In these and other ways bacteria are of inestimable value to agriculture.

The dairy industry is largely dependent for its successful conduct on the control of bacterial presence and bacterial action. It is a commonplace that milk soon sours if kept at a temperature that permits bacterial growth. Uncleanly conditions favor rapid souring because of the large number of bacteria introduced. Milk at room temperature sours faster than milk in an icebox because bacteria grow faster at the higher temperature. If milk is collected or distributed by persons ill with or recovering from certain diseases it may become the vehicle of infection, since the germs of typhoid, diphtheria, and some other infections multiply in milk. Pasteurization of milk, that is, heating milk for 30 minutes to a temperature of 65° C., not only kills the germs that cause souring and so keeps the milk sweet for a longer period, but destroys the germs of disease and increases the safety of the milk for human consumption. Most of the large cities in the United States now require pasteurization of the general milk supply, and as a result milk-borne diseases have been greatly reduced.

In butter-making the "starters" used for the ripening of cream are simply growths of bacteria that have been found to yield satisfactory results. In some places "pure cultures" of bacteria—that is, growths of single species—are used, the kinds that are employed being those that experience has shown to give a particularly desirable flavor or aroma to the butter. It is believed that a high-grade, uniform product may be obtained in this way.

Cheeses, also, owe their individual character in part to the kinds of bacteria and molds that participate in their ripening, in part to the conditions—temperature and other—under which they are manufactured. Thus it is supposed that the quality and uniformity of certain French cheeses are influenced by the con-

stant temperature prevailing in the limestone caverns in which they are customarily ripened. The highly prized characteristic flavors and consistencies of the different varieties of cheese are due to the products of the micro-organisms concerned. Some of these products of bacterial decomposition may be offensive except to the epicure.

Certain other industries are more or less dependent upon bacteria and their relatives, the yeasts and molds. The proper conduct of the fermentations of beer and wine, of the conversion of cider into vinegar, of the preparation of hides for tanning, of the retting of flax, and of similar processes demands some knowledge of bacterial nature and bacterial products. Some of these industries, by controlling the kinds of bacteria and the conditions of growth, are emerging from the stage of rule-of-thumb procedure into that of orderly and stable scientific management. Industrial bacteriology undoubtedly holds possibilities of great future development.

Bacteria as foes.—While there are probably many ways yet unexplored in which bacteria can be, as it were, domesticated and harnessed to various industrial processes for human benefit, it is as enemies of mankind rather than as friends that they have thus far attained the greatest prominence.

It is well known that the destruction of human food by bacterial agency reaches appalling proportions. Meat spoils, milk sours, fruits and vegetables become rapidly inedible, eggs and fish grow exceedingly offensive. Costly or tedious methods of food preservation, by heating, by refrigeration, by salting, smoking, and drying are rendered necessary if food supplies are to be kept over from a season of superabundance to a season of scarcity. As it is, tons of valuable foodstuffs that have taken months of human effort to produce may be destroyed in a day by bacterial activity.

Occasionally definitely deleterious substances are produced In one remarkable instance, the growth of a particular microbe in food gives rise to a poisonous substance which may cause illness

and death. This germ, named Clostridium botulinum, because it was first found in sausage poisoning, occurs in soil in various parts of the world. Its spore stage especially is so resistant that it may survive boiling for a considerable period. When it accidentally finds its way into foods designed for preservation by canning or salting, a few germs may resist the preservative process and retain their vitality. Unfortunately, Cl. botulinum is not dependent upon the free oxygen of the air for its development, but is able to multiply in sealed cans or jars kept at a suitable temperature. The poison thereby produced is exceedingly deadly and has been the occasion of several fatal outbreaks of botulism caused by eating canned meat, spinach, olives, string beans, and the like in which Cl. botulinum had grown. Although very rare, this form of food poisoning has attracted great attention because of the peculiar symptoms and the dramatic type of outbreak. Extensive experiments have shown that even the resistant spores may be destroyed by sufficiently high temperatures obtained by steam under pressure, and the large-scale canning processes are now generally controlled and safeguarded by automatic devices. Although the botulinum spores are strongly heat-resistant the poison of botulism is readily destroyed by boiling for a few minutes, so that the practice of thoroughly heating food removed from a can or jar affords a measure of safety. In point of fact, the contents of cans in which Cl. botulinum has grown almost invariably give evidence to the senses of being spoiled; hence the discarding, without tasting, of apparently spoiled canned food, and the heating of canned food before serving are in themselves practical means of protection. Acid fruits, berries, and vegetables like the tomato have never been known to cause botulism. There is no evidence that Cl. botulinum invades the tissues of the human body. Its poisonous action, like that of the poisonous mushroom, is due wholly to a substance produced outside the body. Botulism is not an infectious disease, occurs less frequently than mushroom poisoning, and may be readily prevented.

Much more common and serious than botulism are the true

infectious diseases produced by bacteria. The specific infections of man and the higher animals now known to be due to bacteria and their allies number several score, among them some of the most destructive maladies to which the human race is liable. If we ask what reasons we have for regarding a specific microbe as the cause of a specific disease, the evidence in most instances is quite compelling. In diphtheria, for example, we find in great numbers in the throat and particularly in the false membrane of diphtheritic patients a rod-shaped micro-organism with a beaded appearance (Fig. 28). The same bacillus is sometimes found in the throats of diphtheria convalescents and of persons who have been in contact with diphtheria patients, but not as a rule in other persons. When an animal is inoculated with a pure culture of this bacillus the true clinical picture of human diphtheria, including the characteristic false membrane, is reproduced. The bacillus can be grown in broth in test tubes outside the body, and after it has multiplied for a few days we find that a poisonous substance or toxin has been produced. By filtering the broth through fine-pored filters the diphtheria bacilli may be strained out of the broth while the soluble toxin passes through in the filtrate. The germfree toxic broth, when injected into an animal like the guinea-pig, will cause the death of the animal with symptoms of diphtheria, and, what is especially significant, the changes observed in the tissues of animals dying after the injection exhibit the same microscopic appearances as those observed in the tissues of children who have fallen victim to a natural diphtheria infection. Moreover, an exceedingly minute quantity of the broth when injected into the skin of a child who has not had diphtheria and is susceptible will cause a slight reddening of the skin at the point of inoculation, whereas a child who has had diphtheria will show no such reaction. This is the so-called Schick test used by health officers for determining what children are susceptible to diphtheria and need immunization. It offers another piece of evidence in favor of the specific character of the beaded bacillus.

Perhaps the most remarkable outcome of the bacteriological

study of diphtheria has been the discovery that the resistance which one attack of diphtheria confers against a subsequent attack—a phenomenon common to many infections—is connected with the presence in the blood of the convalescent of a substance that has an antagonistic action to the diphtheria toxin. This substance which neutralizes the diphtheria toxin in some such way as an alkali neutralizes an acid is called the diphtheria antitoxin. It is because of the presence of antitoxin in the child recovered from diphtheria that the Schick test is negative, that is, that there is no reddening of the skin when a small quantity of toxin is injected.

The formation of antitoxin in the body has been taken advantage of in a way that has had far-reaching practical consequences. A horse inoculated with gradually increasing doses of bacillus-free toxin eventually comes to contain in its body large amounts of diphtheria antitoxin. By drawing off the blood of the horse under aseptic conditions and separating the clear, straw-colored fluid or serum from the fibrin and corpuscles, a large amount of diphtheria antitoxin may be obtained. Processes of concentration and purification are often used to increase the amount of antitoxin contained in a given volume of fluid. The brilliant success attending the use of the antitoxin for the cure of human diphtheria is well known. Not only does the antitoxin from the horse neutralize the diphtheria toxin when mixed with the latter in a test tube, but when inoculated into the tissues of a child suffering from diphtheria the same reaction takes place, the symptoms of diphtheritic poisoning are ameliorated and speedy recovery may follow. The immediate improvement in a diphtheria patient who is inoculated in the early days of the disease is a commonplace of medical experience. The statistics of diphtheria mortality likewise demonstrate in an impressive way the success of antitoxin treatment. For the five years, 1890–94, before the introduction of the antitoxin treatment, the diphtheria death-rate per 100,000 population was very high in most American cities. All but four of the 53 large cities had rates of over 40 and only two had rates under 10.

In 1920–24 no large city in the United States had a rate of over 40 and the highest average recorded in any city was 27.8. Table V gives a few representative instances. In some cases the reduction in diphtheria rates has been even greater than that shown in Table V. New Haven had a yearly average rate of 74.5 in 1890–94, while in 1924 the rate was 1.7.

It cannot be doubted that the larger part of this decrease in diphtheria mortality has been due to the use of the antitoxin treatment. The improvement is still continuing and in view of the method of diphtheria immunization now being put into practice it may be reasonably anticipated that diphtheria will soon become negligible as a cause of death in all civilized countries.

TABLE V

DIPHTHERIA DEATH-RATE PER 100,000 POPULATION IN 1890–94 (BEFORE ANTITOXIN) AND IN 1920–24

	1890–94	1920–24
Boston	112.2	20.2
New York	134.4	14.0
Philadelphia	119.4	16.7
Chicago	117.3	17.5
Detroit	132.9	24.3
Nashville	28.4	8.0
New Orleans	51.3	6.5
San Francisco	82.8	23.0

Even in the face of these facts there are some people who maintain that disease is imaginary, that bacteria are imaginary, and that we are on the wrong track in attempting to prevent and cure infection by such methods as those outlined above. Such persons must be willing not only to deny the significance of all our bacteriological observations on diphtheria and other infections, but must be prepared to question the relations of bacteria to fermentation, decomposition, and other natural phenomena. Is it pure imagination that a can of food will spoil if opened and allowed to stand on the kitchen table, that an apple will decay if the skin is broken, that a deep cut or scratch with a dirty knife on one's hand may cause blood-poisoning if untreated?

Other diseases besides diphtheria are being brought under control as a result of bacterial investigation. It has become clear that each disease is a problem in itself and that methods of cure and prevention applicable in one are not necessarily applicable in others. The co-operation of physicians and engineers, of chemists and bacteriologists, has been enlisted in the campaign against disease.

It is a singular fact that a soluble toxin resembling that produced by the diphtheria bacillus is produced by relatively few bacteria; one of the other best-known instances is the lockjaw or tetanus bacillus. But the precise manner in which most of the disease-producing bacteria effect their injuries is still a mystery. It may be that certain bacteria generate poison when they grow in the animal body but are unable to do this when growing in test tubes; it may be that poisons are liberated when bacteria after enormous multiplication—as that of the cholera vibrio in the intestine—begin to die and disintegrate; or it may be that mechanical factors are largely responsible. In tuberculosis, and to a still greater degree in leprosy, the slow destruction and alteration of the tissues seem to be far more important than any poisonous effect on the whole body. For these reasons the method of antitoxin treatment which has been so brilliantly successful in combating diphtheria has only a limited application.

Typhoid fever and Asiatic cholera, in which infection is produced by swallowing the specific germs, may be most effectively attacked by keeping the germs out of food and drink. Sewage-polluted water supplies have been found one of the main vehicles of these infections; consequently measures such as protecting our streams and lakes against contamination and purifying our water supplies by filtration or chlorination have proved of great value in reducing the amount of typhoid, and have practically robbed cholera of its terrors for the larger part of the world. In India, with its crowded population and generally contaminated water courses, the latter disease still prevails. Milk-borne typhoid in the United States has been largely eliminated by the general

introduction of the process of pasteurization, now required by ordinance in most large American cities. Persons particularly exposed to typhoid, such as soldiers in war time, hospital nurses, and travelers in countries where the disease is still common may be protected to a great extent by taking the anti-typhoid inoculation. The "typhoid vaccine" which is composed of killed typhoid bacilli in carefully graded doses has nothing in common with the antitoxin of diphtheria. It has little or no curative action and merely protects against infection. The history of the American Army in the Great War demonstrates the remarkable effectiveness of this method of protection. The deaths of soldiers from typhoid numbered only a few hundred, while if they had occurred at the same rate as in earlier wars in which inoculation was unknown, there would have been more deaths from typhoid than from all the bombs and bullets of the enemy. Little advance has been made in curing typhoid; the case fatality—that is, the number of deaths per hundred cases—is now just about what it was a generation ago, but during the same period the number of typhoid deaths in proportion to the population has been lowered by as much as 90 per cent in many of our American cities. The reduction of typhoid has been brought about by preventive measures, as that of diphtheria by curative.

Pulmonary tuberculosis or consumption presents quite a different problem. Under existing conditions of civilized life infection can hardly be avoided. Indeed, city dwellers are probably almost universally infected at some period of their lives; but the great majority recover, often without knowing that such an infection has occurred. The fact is that under hygienic conditions human resistance to serious tuberculosis infection is high, and that most individuals are successful in preventing the spread of the bacteria in their tissues. In this disease we can hardly hope at present to escape contact with the tubercle bacillus, especially if we breathe much city dust or ride in crowded vehicles; no antitoxin or similar remedy has yet been produced; indeed, as already stated, the damage done to the body by the tubercle bacillus does

not seem to be due to any acute poison such as that produced by the diphtheria bacillus, but to a much slower, long-continued action. It may be that some chemical substance will be found which, when introduced into the body, will stay the development of the tubercle bacillus, and many experiments have been made and are still being made to try out this possibility. Up to the present our best means of controlling tuberculosis has been the utilizing of the natural powers of resistance, especially by strengthening this resistance through proper nutrition, rest, fresh air, and other familiar measures. The segregation of advanced cases of consumption in sanatoria has also probably been of value in diminishing the opportunities for repeated and massive infection of relatives and fellow-workers. Education in personal hygiene and warnings about the danger of disseminating bacilli in the sputum have also been important factors in the campaign against tuberculosis. In the past 40 years there has been a great decline in the death rate from this disease in nearly all civilized countries. It seems fair to attribute this in part to the general improvement in the conditions of life which has raised the level of resistance throughout the population, in part to the effect of the educational campaign against tuberculosis, and in part to the proper provision for the advanced cases of consumption, which from the standpoint of dissemination of large numbers of bacilli are the most dangerous.

In still another direction some progress has been made in controlling human infection. The attempt to find some chemical compound which shall kill the parasite while leaving the host unharmed has been successful in a few cases. Perhaps the most notable of them is malaria, a disease due to a minute protozoön. As everybody knows, quinine in suitable doses destroys the malarial parasite without injuring the patient. A compound containing arsenic has been found of great value in treating certain spirochetal diseases. The use of aniline dyes in combating certain forms of suppuration has also been successful. It may be that the number of chemical substances proving chemical affinity for specific bacteria will be greatly added to by researches now in progress.

These examples of bacterial infection in man illustrate both the diversity of the problems of prevention and cure, and the success that has been reached in some instances. In other diseases little progress has been made. Against colds, influenza, and the pneumonias we are at present almost, if not quite, as helpless as we were before the share of bacteria in these infections was so much as suspected. In some diseases the causal microbe has not been surely discovered. Nearly every infectious disease bristles with problems that demand solution.

Like man, domestic animals and plants suffer from bacterial infection. The losses among cattle, swine and poultry, horses and sheep, reach very high figures and constitute a heavy burden on agriculture. Hardly less serious are the bacterial diseases of food plants, the "wilts," "rots," and other infections which, added to losses caused by the higher fungi and by insects, make the raising of food crops a precarious occupation. Just as in human infections, however, knowledge is being gathered, little by little, which is sure in the long run to make the task of the stockman and the farmer easier and surer. The famous words of Tyndall are worth repeating: "We have been scourged by invisible thongs, attacked from impenetrable ambuscades, and it is only today that the light of science is being let in upon the murderous dominion of our foes."

SELECTED REFERENCES

1. Edwin Oakes Jordan, *A Textbook of General Bacteriology* (8th ed., Philadelphia: W. B. Saunders Co., 1924), 718 pp., 179 illus.

2. Jean Broadhurst, *Bacteria in Relation to Man, A Study Text in General Bacteriology* (Philadelphia: Lippincott, 1925), 306 pp., 147 illus.

3. Arthur I. Kendall, *Civilization and the Microbe* (Boston: Houghton Mifflin & Co., 1923), 231 pp., 28 illus.

4. Samuel J. Holmes, *Louis Pasteur* (New York: Harcourt Brace & Co., 1924), 246 pp.

CHAPTER VIII

EVOLUTION OF THE PLANT KINGDOM

MERLE C. COULTER

Astronomers have explored and described a universe in which the unit masses and the spaces which they occupy, as well as the rates at which they move, make us feel exceedingly minute ourselves. Geologists have thrown on the screen a moving picture of the history of the earth's surface in which the chapters occupy such tremendous periods of time as to make us, by comparison, decidedly temporary. These sciences give us a deep feeling of humility, and at the same time inspire us with the concept of orderly change, or evolution, throughout time and space. We now propose to focus the microscope of science a little more closely upon the particular spot in time and space that we ourselves occupy, and consider a particular sequence of events that has beer taking place upon the face of the earth since life first appeared. Here, too, in the history of the plant kingdom, is the same unifying principle of evolution, or orderly change.

The nature of the information.—The ideas that botanists hold respecting the evolution of the plant kingdom are based largely upon comparative studies of the structures of plants now in existence. Two plants may be very similar in all of their more fundamental characteristics, but may differ in some details. One infers that these two are related by descent, since otherwise their similarity is difficult to comprehend. It is the similarity that suggests common ancestry, and it is the nature of the difference between the two that suggests which is the more primitive type Type A may be simpler than B; it may lack something that B possesses. Accordingly, it is inferred that A is the ancestral type and B the modified descendant; that is, the common ancestor of the two resembled A, and some of its descendants have remained

relatively unchanged, while others, which may have come to live under somewhat different conditions, have gradually become modified to the extent illustrated by B. This is essentially a matter of inference and not of demonstration. Using this type of procedure, the family relationships of different members of the plant kingdom are sketched, and all are placed somewhere upon a general family tree.

If every type of plant that ever existed upon the earth were still present somewhere, it would be a relatively simple though tedious problem to construct a complete family tree for all members of the plant kingdom. Unfortunately this is not the case; many of the pre-existing types have become extinct, and often we look in vain for living representatives of the ancestors of our present-day plants. These are the "missing links" that make the construction of a family tree so troublesome. Such gaps are often filled in by vigorous efforts of the imagination; botanists construct as best they can an imaginary picture of the "missing links," so as to complete the sequence of steps in the evolution of the plant kingdom. Obviously such a practice is mainly guess-work, but, like many such hypotheses, has been very useful in organizing subject matter and stimulating research.

Missing links are sometimes found in the form of fossils. Fossils of plants known to have lived at earlier periods often provide a very reliable and satisfactory picture of ancestral types. In this field, however, the zoölogist has a great advantage, since animals are more often preserved as fossils than are plants. This is mainly due to the fact that animal bodies commonly contain hard, resistant structures, while plants, on the other hand, are relatively tender things that fossilize poorly, and this is particularly true of the more primitive types. Hence the record of the rocks reveals practically nothing of the earlier chapters in the evolution of the plant kingdom. For these, therefore, we must rely upon the types of plants still in existence, plus a liberal measure of scientific imagination.

In spite of the many uncertainties, however, botanists are

convinced that the plant kingdom has developed, in an orderly manner, from simpler, primitive ancestors to the more complex modern types that are conspicuous today. It is a story of progress from simple to complex, from generalization to specialization, from a humble, restricted abode in certain limited situations to a complete occupancy of the surface of the earth. Starting in relatively few locations, plants gradually spread to new surroundings. They could accomplish this only by becoming adapted to new conditions. It is this adaptation to new conditions that we call evolutionary progress.

The attempt will be made here to sketch the main steps in evolutionary progress. This can be done by selecting certain types of plants which represent the successive advances that have been made. Four major steps must be taken, corresponding to the four major divisions of the plant kingdom.

I. PRIMITIVE WATER PLANTS (THALLOPHYTES)

There is rather general agreement that the plant kingdom made its start in the water. Certainly our simplest plants can live only in a medium of water, and fresh water, at that. The ability to live in salt water evidently came later.

The simplest plant of all.—About the simplest plant known (*Gloeothece*, Fig. 32, *A*), is one whose body consists of a single cell, microscopic in size. The essential part of this cell is a sphere of that remarkable living substance known as protoplasm. So far as we can tell, this protoplasm has the consistency of a thin jelly, though in appearance it is finely granular rather than clear, and is bluish-green in color. The protoplasm is surrounded by a transparent gelatinous cell wall, which must provide some sort of protection for the living substance. The ordinary microscopic preparations reveal no differentiation within the cell, no apparent division of labor; the protoplasm appears to be practically homogeneous, and must have the power of carrying on all the essential life functions.

Certain dissolved materials enter through the wall, and from

these the protoplasm manufactures food for itself, using light as a source of energy in the process. This food is transformed into more protoplasm, and the cell grows, stretching the elastic wall. When it has attained a certain size it pinches in two in the middle. Thus two daughter protoplasts are formed by division of the parent. These daughters will surround themselves with walls, and in all respects are similar to the parent that produced them. They are now separate individuals, capable of carrying on independent existences. Reproduction has occurred; a single parent has produced two offspring. Yet the parent has not died, but continues to exist in its progeny. Immortality of this sort is characteristic of simple plants.

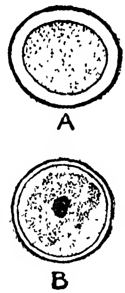


FIG. 32.—(*A*) The single-celled individual of *Gloeothece;* protoplasm apparently homogeneous. (*B*) The single-celled individual of *Pleurococcus*, showing cell organs; nucleus in the center, surrounded by cytosome; the irregular chloroplast can be distinguished as the most concentrated part of the cytosome.

To summarize: In this lowly form, the individual consists of a single cell of apparently undifferentiated protoplasm, and reproduction is accomplished by the simple process of cell division.

Division of labor.—From such a primitive condition as this all other plants have descended. A significant evolutionary step was taken when differentiation and division of labor occurred within the protoplast. There is a simple one-celled plant (*Pleurococcus*, Fig. 32, *B*) which somewhat resembles the one just described, but differs strikingly through the possession of cell organs. Here the protoplasm is not homogeneous, but separate constituents are distinguishable. In the center is a small, spherical, concentrated bit of protoplasm known as the "nucleus." This nucleus is evidently more concentrated than the rest of the protoplasm, which is now designated by the term "cytosome." Furthermore, the cytosome itself is not perfectly homogeneous, but includes a more concentrated mass of the living substance known as the

"chloroplast." All these cell components are made of protoplasm, but nucleus and cytosome are visibly distinguishable, while the chloroplast stands out plainly as the most concentrated part of the cytosome.

The significant thing is that division of labor has occurred. The function of manufacturing food, which was previously performed by the generalized protoplasm, together with its other duties, is now turned over entirely to the chloroplast. Correlated with this, we find that the green coloring matter, which is essential to food manufacture, is now restricted to the chloroplast. It is the rest of the cytosome which uses this food and transforms it into more protoplasm, and it is the nucleus which at cell division distributes the hereditary qualities in orderly manner. Specialization has occurred within the cell, a division of labor among specialists, with the result that the cell functions can be carried on more efficiently than before. At cell division each of the cell organs is divided (by the process of "mitosis" which was described in an earlier chapter), so that the daughter cells start life with the full equipment. All of the higher plants show essentially this cell organization.

A many-celled individual and how it reproduces.—The next plant to be considered (*Ulothrix*, Fig. 33, *A*) illustrates three further steps in advance. In the first place, its body no longer consists of a single cell, but of many cells which are attached end to end in a filament. This is a many-celled individual, since the cells are mutually dependent and cannot live successfully as separate individuals. Each cell, however, has its own nucleus and cytosome with the chloroplast. The lowermost cell puts out sucker-like processes which cling to some object at the bottom of the stream of water in which the plant lives.

The other two advances shown in this form have to do with reproduction. When a cell of the filament divides, its division occurs only at right angles to the axis of the filament. Cell division can thus increase the length of the filament by adding to the total number of cells, but this is merely growth of the individual

and is not reproduction of a new individual. For reproduction, some other provision must be made. This is accomplished by "internal division." Under certain conditions the protoplasm within each cell of the filament will shrink away from the cell wall to form a relatively concentrated sphere of material on the inside. This sphere of naked protoplasm will then divide into two equal parts, and each of these may divide again, forming a total of four (more or less) units, each of which is a naked protoplast. These are called "spores." Each has its own nucleus and cytosome. About this time the old cell wall breaks, allowing the spores to escape into the surrounding water. The spores become somewhat pear-shaped, and, at the pointed ends, there develop minute hairlike processes ("cilia"), which vibrate rapidly and propel the spores through the water.

After swimming around aimlessly for some time, the spores come to rest at the bottom of the stream. Here they behave exactly as one might expect any cell to behave; they grow and divide repeatedly to form a filamentous individual, the lowermost cell attaching itself to the substratum. Thus a new individual is produced by a spore. Fundamentally, however, the spore has no new capacities. It produces a new individual by cell division, a process which any cell may carry on. The effectiveness of the spore in accomplishing reproduction lies in the unique opportunity that is provided by its separation from the parent individual.

Any cell in a filament may produce spores, and commonly all cells do so at the same time, so that the discharge of spores leaves behind a lifeless string of empty cells.

The origin of sex.—Still another important advance is shown by this same plant. Under hard conditions, such as those that occur at the end of the growing season, the cells of the filament divide internally, as in the production of spores, but now the process is carried further. A greater number of internal divisions occurs, so that the resulting protoplasts are smaller and more numerous. These are known as "gametes," and are destined to behave very differently from spores. They are discharged into

the water where they swim about in erratic manner for some time. All the gametes are identical in appearance, and are like the spores save in size. Yet they finally come together in pairs, the two gametes rapidly fusing to form a single protoplast. This event marks the origin of sex, the modern method of reproduction in both plant and animal kingdoms, a method which is of enormous significance in heredity and evolution. These primitive sex cells,

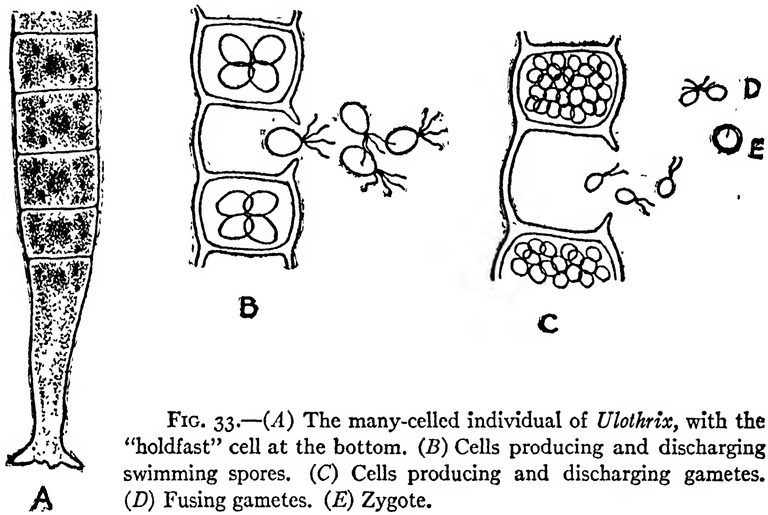


FIG. 33.—(*A*) The many-celled individual of *Ulothrix*, with the "holdfast" cell at the bottom. (*B*) Cells producing and discharging swimming spores. (*C*) Cells producing and discharging gametes. (*D*) Fusing gametes. (*E*) Zygote.

the fusing gametes, cannot be distinguished as male and female; yet the fusion itself is unmistakably a sex act.

The product of the sex act is a simple protoplast known as the "zygote," which is capable of producing a new individual.

To summarize: The plant just considered illustrates three fundamental steps in evolutionary progress: (1) the origin of the many-celled body, (2) the origin of the spore method of reproduction, and (3) the origin of sex.

Eggs and sperms.—Relatively little progress was made in body structure among the higher plants of this first division. Unbranched filaments were in some forms replaced by branching filaments (e.g., *Cladophora*) and even a simple platelike body was

achieved (*Ulva*). For the most part, however, these bodies remained one cell thick, exposing every cell to the surrounding water medium, and effecting no noteworthy differentiation of body regions or tissues.

Methods of reproduction, on the other hand, became rather specialized. The sex act in particular underwent quite a series of significant modifications. One of the first of these was the differentiation of gametes into male and female. In the beginning all gametes were small and actively swimming. From this starting-point it would be possible to arrange a series of type plants showing a gradual increase in size and loss of motility in one of the gametes, accompanied by slight diminution in size and maintained motility in the other. The final member of the series (e.g., *Oedogonium*, Fig. 34, *A*) would exhibit an extremely large and passive female gamete, or "egg," and a very small and active male gamete, or "sperm." For the sex act to be accomplished here, it is necessary that the sperm travel to the egg. This is expedited by the fact that the egg exudes a chemical which attracts the swimming sperm. The two gametes then fuse as before; the sperm is said to "fertilize" the egg. As before, a zygote results, which has the capacity of producing a new individual.

This differentiation of gametes has, of course, some greater significance than merely to show us which is male and which female; it must convey some real advantage to the plant. The advantage is not difficult to see. As we all know, the success that an individual makes of its life depends in large part upon how successful a start is made. A vigorous growth early in life is a great advantage. The egg is large and passive because it is stored with a great amount of nutritive material. This nutriment is included in the zygote and becomes available to carry the young individual over the critical early period of its life.

It should be noted, however, that the great size of the egg is due to the cytosome alone. Its nucleus is no larger than that of the sperm, and correlated with this is the fact that the hereditary contributions of male and female parents are equal.

Male and female individuals.—Still another advance is made in sexual reproduction with the differentiation into male and female individuals. Heretofore male and female gametes have been produced by the same plant body. Now (e.g., *Spirogyra*, Fig. 34, *B*) male and female individuals are recognized, one producing only the sperms and the other only the eggs. In a very fundamental sense this is the culmination of sex evolution, a perfecting of the arrangement whereby sex conveys its main advantage. In a later section of this book (chap. xiii) it will be explained how sex expedites evolution, and how this is rendered most effective by the sexual differentiation of individuals.

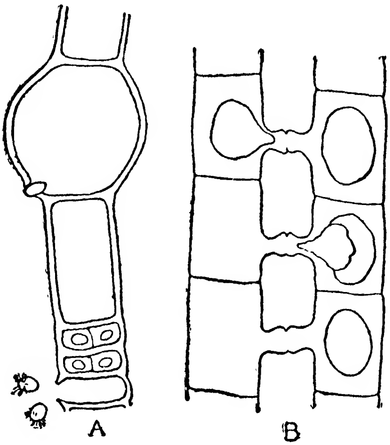


FIG. 34.—(*A*) *Oedogonium*, with swimming sperms being discharged from cells lower in the filament. One of these is entering a cell higher up, which contains a large, passive egg. (*B*) *Spirogyra* at the time of fertilization. The individual on the left is male; all of its protoplasts act as sperms and pass through the connecting tubes to fuse with the passive eggs of the female individual on the right; three steps in the process are shown.

To summarize: This first subdivision of the plant kingdom contributes relatively little to the evolution of the plant body. Cell organs are differentiated, and many-celled individuals of simple body form and structure. Reproduction, however, makes enormous progress. Starting with reproduction by simple cell division, the spore method is evolved, sex is originated, gametes become differentiated, and a culmination is reached with the sexual differentiation of individuals.

Space limitations permit no more comprehensive treatment than the foregoing. The thousands of types of seaweeds, and the fungi, those weird colorless plants which dwell parasitically upon

other plants and animals and which are consequently of great economic significance, must be dismissed without further description. The bacteria, which also are thought to belong to this first great group of plants, are of such tremendous economic importance that a special chapter (vii) of this book has been devoted to them.

II. AMPHIBIOUS PLANTS (BRYOPHYTES)

The second division of the plant kingdom, containing mosses and their allies, takes the notable step of acquiring the land habit. Life on the land is very hazardous for those primitive plants whose bodies are constructed for a water medium. On land they are subjected to the fatal evaporating power of the air, which destroys protoplasm unless some protection is provided. Accordingly, the earliest adaptations to appear among plants of this division are such as to provide a protection against drying out.

Acquiring the land habit.—Starting with the simple sheet-like body which occurred in certain ancestral types, three early modifications were made by these amphibious plants: (1) A compact body was constructed, several layers of cells thick, reducing the relative number of cells which were exposed to the drying influence of the air. (2) A prostrate habit was assumed. By lying flat upon the muddy banks onto which they had emerged, these plants presented only about half of their surface to the air, and at the same time maintained considerable contact with a source of water. (3) A protective "epidermis" was developed. This was really the first differentiation of a specialized tissue. The cells of the outermost, or skin, layer relinquished the rest of their responsibilities and became specialists at protection. This was accomplished by fitting compactly together, thickening the outermost walls, and impregnating them with a waterproofing material. All exposed parts of higher plants are provided with this protective epidermal layer.

Fortified in this manner, the amphibious plants crept out farther upon the land surface, and gradually became able to

withstand its hardships more successfully. The primary necessity in plant life is to carry on food manufacture. This work (known as "photosynthesis,") is done by the chloroplasts; the necessary raw materials are carbon dioxide and water; the source of energy is the light; and the product of the process is carbohydrate food. It was not difficult to construct an epidermis sufficiently transparent to allow the passage of light to the working cells beneath, but the carbon dioxide problem was more serious. Land plants must take carbon dioxide directly from the atmosphere. The difficulty, therefore, is quite obvious, since that same epidermis which prevents drying out by evaporation makes it impossible for carbon dioxide gas to enter. Such contradictory demands as these could be satisfied only by some sort of compromise, which was effected in the following manner. To provide for entrance of carbon dioxide, small openings were left, here and there, in the epidermis. These openings were, of course, a menace as well as a benefit, since they permitted loss of water vapor and consequent drying. This would be particularly true at times when the atmosphere was very dry and the rate of evaporation at its maximum. This danger was reduced, in a rather neat way, by endowing those cells which surrounded the openings with power to close the openings when humidity was low and to open them when humidity was high. Thus entrance of carbon dioxide and the resulting food manufacture was permitted only when it was safe.

The compact bodies and prostrate habit inevitably brought another type of specialization. The energy provided by light for food manufacture is pretty well extracted by the upper few layers of chloroplast containing cells. Food manufacture could be carried on poorly at best by the shaded cells beneath. Accordingly, food manufacture was carried on by the cells of upper regio and other duties were performed by the cells further dow Obviously the most fitting function for those lower cells was that of providing water for the entire plant. Water is needed not only for food manufacture, but also to maintain the proper life

conditions for protoplasm in general. To offset the inevitable loss by evaporation above, an almost continuous supply must be provided from below. The plants under consideration lay upon a moist substratum, such as a muddy river bank. From this they could soak up water through their lowermost cells. Under the circumstances, the cells of the lower epidermis must be thin walled. It is further evident that the rate of absorbing water is proportional to the area of the absorbing surface. The surface was increased enormously by having occasional cells of the lower epidermis extend themselves in long hairlike processes which penetrated the moist mud beneath. These were not, technically, "roots," but had the same fundamental capacities as the roots of higher plants (Fig. 35).

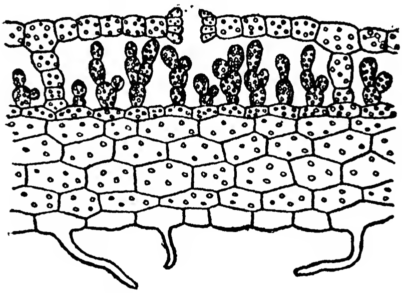


FIG. 35.—A section of the body of one of the Bryophytes. CO_2 enters the air pore and circulates through the chamber beneath. The loosely arranged cells within this chamber contain chloroplasts and manufacture food. The lowermost cells, with their protrusions, absorb water from the moist substratum.

The foregoing characteristics were the essentials of body organization that appeared in plants of the second division. All are clearly occasioned by the acquiring of the land habit. The specialized tissues and body regions that have been mentioned are simply the inevitable adaptations that had to be made in solving the problem of life in a medium of air. Later members of this group of plants developed bodies that were arranged somewhat differently and even elevated slightly from the surface of the ground.

It would be surprising indeed if no corresponding changes had taken place in reproductive processes. Reproductive changes did, in fact, occur, and these too may be interpreted as adaptation to land conditions. Reproductive organs, of course, became many-

celled, since spores and gametes had to be protected by an epidermal layer, but what is more fundamental is the change that took place in the general program of reproduction.

The sex process had come to stay. It brought such a tremendous advantage that no species could afford to dispense with it. The sex act had been accomplished in primitive plants by the swimming of the sperm through a water medium until it arrived at the egg. All of the moss plants maintain swimming sperms, and consequently can carry out the sex act only during rain or heavy dew, when a continuous water passage is provided between male and female sex organs. Since plants are now to live in an air medium, one might expect that some other means than swimming would be provided for the movement of the sperm. Easier said than done! The fact is that it took plants millions of years to provide new means of locomotion for the sperm.

Another problem connected with reproduction lies in the matter of distributing the species. Every progressive species must be endowed with some means of distributing its individuals over an ever increasing territory. Most animals accomplish this by the obvious means of having the individuals themselves move. Plants, however, have stationary individuals (for the most part) and can accomplish distribution only by having the reproductive parts scattered. This was accomplished in the primitive plants by swimming spores. In the moss group, however, this plan is out of the question, since spores could not swim in an air medium. Consequently the spores are modified. Their swimming apparatus is removed, and they are covered with a heavy cell wall, as a protection against drying out. Set loose at as great a height as the small stature of the moss plants will permit, these light spores are carried by chance air currents, and such of them as happen to light in moist and otherwise favorable spots succeed in producing new individuals.

Alternation of generations.—But reproduction is still more involved. To preserve the benefits both of the sex act and of spore reproduction, the mosses combine them in the same life-cycle.

This results in the phenomenon of "alternation of generations," which will now be described briefly.

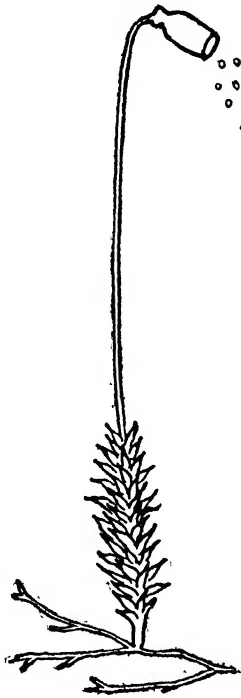


FIG. 36.—Gametophyte and sporophyte of moss. The little thread at the bottom, with the leafy, erect branch, constitute the gametophyte generation, which is green and manufactures its own food. At the top of the leafy branch, tiny sex organs have already effected fertilization. The resulting zygote has grown into a sporophyte, which is now parasitic upon the gametophyte. The foot of the sporophyte is buried within the gametophyte, but stalk and capsule are visible, the latter shedding spores, which have the capacity to produce new gametophytes.

Starting with a green, food-manufacturing body corresponding to that which was first described, sex organs are produced upon this in protected regions where a film of water is frequently available. Fertilization is then accomplished by the swimming of a sperm to an egg, and this results in a fusion cell, or zygote. In the terminology of reproduction, this plant which produces the gametes and effects fertilization is known as the "gametophyte," which simply means "gamete-producing plant." The surprising thing is that the zygote then proceeds to produce an entirely different sort of plant. This second plant bears no resemblance to the gametophyte. It is quite different in form and structure, and, having practically no green chloroplasts, is incapable of manufacturing its own food. Consequently it must live parasitically upon the gametophyte in order to live at all. Since its sole function is to produce the spores, it goes by the name of "sporophyte," or "spore-producing plant." One may picture this sporophyte as consisting of three organs: (1) a "foot" sunk into the tissues of the gametophyte to extract nutrition therefrom, (2) a

long "stalk" to elevate the spores to a more favorable position for discharge, and (3) at the upper end of the stalk, a "capsule," or spore-container, from which the spores are liberated (Fig. 36). Each of these spores is capable of producing the gametophyte, thus completing this interesting life-history which is summarized in the following formula:

$$\text{Gametophyte} \begin{array}{c} \diagup \text{ egg } \diagdown \\ \diagdown \text{ sperm } \diagup \end{array} \text{zygote–sporophyte–spore–gametophyte}$$

All of the higher plants reproduce through this same method of alternation of generations.

To summarize: The second subdivision of the plant kingdom acquires the land habit, and adapts itself to life in an air medium through the differentiation of certain tissues and body regions, and through reproduction by alternation of generations.

The "failure" of the bryophytes.—Interesting and adaptive as the characteristics of these plants may have been, in a very real sense they were doomed to failure. A radical change was necessary before plants of any magnitude could be constructed. One of the reasons for this appears in the following considerations.

The three critical items in the life of a land plant are, (1) food manufacture, (2) fertilization, and (3) distribution of spores. To carry on a maximum of food manufacture, exposure is necessary; plants must rise from the soil and expose a large area of green leaf surface to the sunlight. Fertilization, on the other hand, is successful only under the opposite conditions; moisture is necessary for the swimming of the sperm, and this is readily available only near the surface of the soil. Distribution of spores is most efficient under conditions of exposure, where the spores can be liberated at a considerable height from the ground. Without attempting to analyze the details further than this, it can be pointed out that the arrangement which prevails in moss plants is obviously a maladjustment. Fertilization and food manufacture, with their contradictory demands, are combined in the gametophyte generation. Large plants can never be developed upon such a plan. If,

however, the responsibility for food manufacture be turned over to the sporophyte, the demands for exposure will be combined in the same generation, and large plants can be developed. This prophecy is fulfilled by the next division of the plant kingdom, where large green sporophyte bodies first appear.

III. FIRST WOODY PLANTS (PTERIDOPHYTES)

As anticipated in the last section, further progress in the development of the plant body is made by the sporophyte generation. In this group we find such types as the ferns, whose sporophytes have shaken off their early dependency upon the other generation and are now conspicuous green plants. It is this independence of the sporophyte generation that constitutes the major contribution to the advancement of the plant kingdom made by the ferns and their relatives.

The body machinery of a woody plant.—The plant body increases in size, rises from the soil, and exposes large leafy portions to the sunlight. Greater exposure brings with it, of course, an increased danger of drying out. The new adaptations provided to offset this consist of a differentiation of the plant body into three distinct regions with separate functions, together with the introduction of a new highly specialized tissue for rapid water conduction. The three body regions referred to are familiar to everyone: (1) leaves, to provide a large green surface for food manufacture; (2) stems, to elevate and display the leaves to the sunlight, and (in the earlier woody plants) to scatter spores more widely; and (3) roots, to penetrate the soil and take up water for the aerial parts. The new tissue provided is likewise quite familiar, being what we all refer to as wood. The microscope reveals that wood consists of a mass of hollow, thick-walled tubes. Elongated cells have thickened their walls and then died, leaving no protoplasm to clog the pipe so constructed. The end walls between successive cells have been dissolved away to provide a continuous passageway. This wood tissue is continuous from one end of the plant to the other, and its business is water conduction

Water (and certain dissolved salts, such as nitrates, sulphates, and phosphates), entering the roots, is delivered into the lower ends of the conducting system. From here it is sent upward into the wood of the stem. From various levels of the stem, local deliveries are made by means of small strands of woody tissue sent out into the leaves. Here the strands are divided and branch repeatedly, constituting the "veins" which we see in the leaf. These veins are ramified through the leaf so perfectly that almost every leaf cell has water delivered practically at its doorstep. Obviously it is these leaf cells that are using the most water, both for food manufacture, and to supplement the loss by evaporation (Fig. 37).

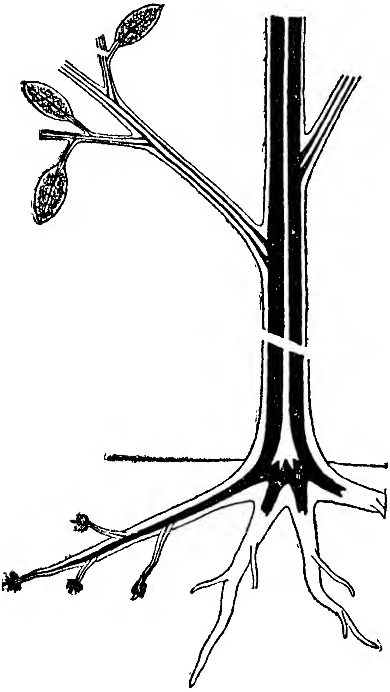


Fig. 37.—Diagram illustrating course of vascular tissue in a tree. The black strands, composed of **wood,** and a few phloem tubes, convey water and food as described in the text.

In addition to the conduction of water and salts upward from the soil, provision must also be made for downward conduction of carbo-hydrate food from the leaves, where it has been manufactured, to other parts of the plant which must be fed. Of course, the water-conducting tubes cannot accommodate this two-way traffic. Hence another set of tubes (known as "phloem") is provided for food conduction. For convenience, the two types of tubes are always associated. Wherever the wood tubes are conducting water rapidly upward, beside them lies this other set of tubes conducting food slowly downward.

These are the essentials of body organization in woody plants. It is upon this same plan that the trees of our forests were later constructed, some towering to a height of about four hundred feet. In these very large plants, of course, a great amount of wood is provided, both for the conduction of water and to lend rigidity to the stems.

Reproduction in ferns.—When it comes to reproduction, however, the ferns make no serious changes in the alternation-of-generations program which appeared in their mosslike ancestors. The sporophyte body, as indicated, is radically different in appearance and construction, but this difference is a function of food manufacture and not of reproduction. The fern sporophyte produces simple spores upon the under surface of its leaves, whence they are discharged and carried about by chance air currents. Those that light upon moist soil produce gametophyte bodies, and these bodies are very much like the gametophytes of the last group. Small, flat, green affairs are these, living quite independently of their parent sporophyte. One who questions the justification of visualizing two distinct generations in the life-history is answered by the ferns, where sporophyte and gametophyte are mutually independent.

Upon these little gametophytes, sex organs are produced, and fertilization is effected, as before, by the swimming of the sperm to the egg. The resulting zygote grows into a sporophyte plant (Fig. 38).

To summarize: This group contributes enormously to the progress of the plant body. The sporophyte generation, which is now independent, grows to be a large plant through the specialization of root, stem, and leaf regions, and the woody, water-conducting tissue which runs through them.

IV. SEED PLANTS (SPERMATOPHYTES)

This last group of plants may be characterized by a number of superlatives:

1. That they are the most advanced and most complex goes without saying, since they constitute the culmination of the evolutionary sequence that has been sketched.

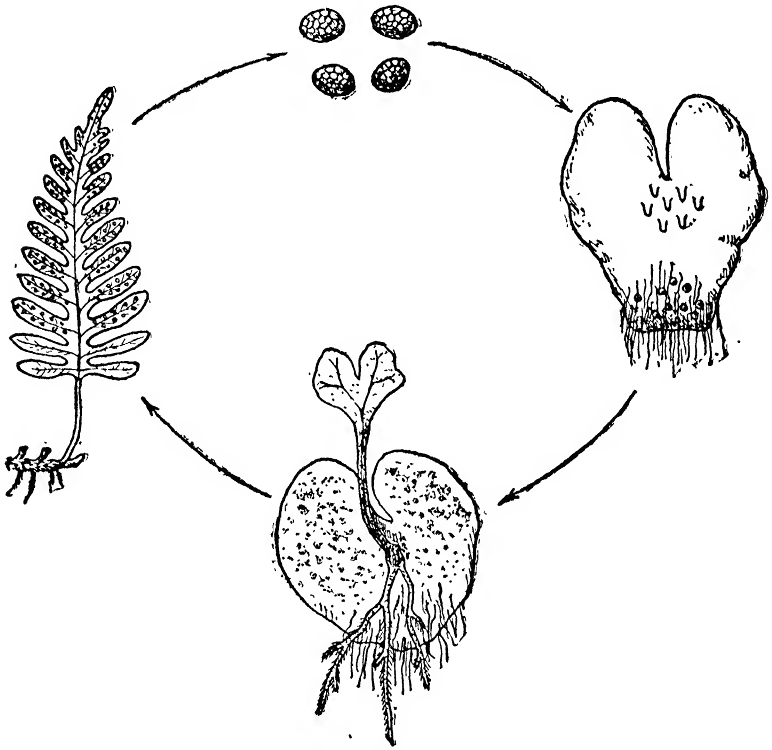


FIG. 38.—Diagram of life-cycle of fern: left, sporophyte body, with underground stem and roots, and large, compound, aerial leaf. Top, spores that have been produced on the lower surface of the sporophyte leaf. Right, small gametophyte produced by spores, showing the lower surface which carries the sex organs. Bottom, young sporophyte growing from zygote that has been produced on lower surface of gametophyte.

2. That they are the most recent is not only inferred from their evolutionary position, but demonstrated by the fact that they appear last in the geologic record.

3. That they are most diversified is to be expected of such an up-to-date assemblage, and is clearly recognized by the variety

in the common natural panorama, which reveals to the eye seed plants and only seed plants.

4. That they are economically most important is not only because they are the basis of our food supply, but also because of the wood, drugs, fibers, paper, and other textiles they provide.

Variation in the plant body.—Here the sporophyte body maintains the same fundamental plan that was developed in the last group. Roots, stem, and leaves, with woody conducting tissue running throughout, are still the essentials of body organization. Details, however, are perfected, and an infinite variety of different forms appears. There are approximately 150,000 different species of seed plants, living under the widest range of environmental conditions and showing corresponding adaptation. Seed plants are classified as trees when the stem is large and erect, as shrubs when the stem is smaller and bushy, and as herbs when the stem is tender, with woody tissue very much reduced. Certain stems sprawl horizontally over the surface of the earth or even remain buried beneath the surface, sending into the air nothing but the leaves. Other stems assume a climbing or vinelike habit, while some even perch upon other plants, and maintain no soil connections of their own. Some seed plants can withstand the rigorous climate of very high altitudes and latitudes, though there are many more, of course, which can live successfully only under tropical conditions. It is the presence of available water that determines the distribution of plants more than does any other single factor, but there are some that live successfully in desert regions. These, of course, have highly developed waterproofing layers, and sometimes maintain large water reservoirs within their own bodies. At the other extreme are types which revert to life in a water medium. These, however, retain the essential characteristics of seed plants, and do not return to the body plan of their remote, water-inhabiting ancestors. In temperate regions the winter season presents a problem which is solved either by developing leaves with high resisting powers, as in evergreens; or by shedding the leaves at the end of the growing season; or by having

the entire plant die each fall and a new generation produced the following spring from the seeds which have wintered over. It is by such adaptations, and by many others, that seed plants have made such successful conquest of the land surface.

Since nature can produce so many types, should not man himself be able to effect much the same thing? Actually man has been doing exactly this for many centuries. Our agricultural plants of today have all been made to order. Unconsciously taking advantage of the evolutionary capacities of plants, the early agriculturists directed this evolution along such lines as to make their crop plants better adapted to human needs. In more recent years a fuller understanding of the laws of heredity has made possible a much more rapid progress in the improvement of commercial varieties. Thousands of the types that we see today possess characteristics that have been evolved under man's guidance.

The life-cycle of seed plants involves the customary alternation-of-generations program, but there are certain modifications which culminate in the production of flowers and seeds. Obviously all seed-plants possess seeds, and most of them produce flowers as well. There are certain more primitive groups, small in terms of the number of species contained, but usually very large as measured by the size of their bodies, which possess seeds but not flowers. Most conspicuous of these are the soft-wood trees, such as pines, where cones take the place of flowers. Chronologically the cone comes first, being the precursor of the flower which appears among the most modern seed plants.

The flower and how it functions.—It will be impossible here to explain all of the details of reproduction in a flowering plant. All that can be attempted is a rough sketch of the main events. The conspicuous plant body is the sporophyte generation. At maturity this body puts forth reproductive structures in the form of flowers. A typical flower possesses four sets of parts: (1) On the very outside lie the "sepals," which are usually green and leaflike, and serve to protect the inner regions while the flower is still an unopened bud. (2) Next inside come the "petals,"

brightly colored and attractive to insects, which play an important rôle in the reproductive process. (3) Then come the club-shaped "stamens," which are filled with small spores ordinarily referred to as "pollen grains." (4) On the very inside is the "pistil." Within its swollen base are bodies which later will become seeds (Fig. 39).

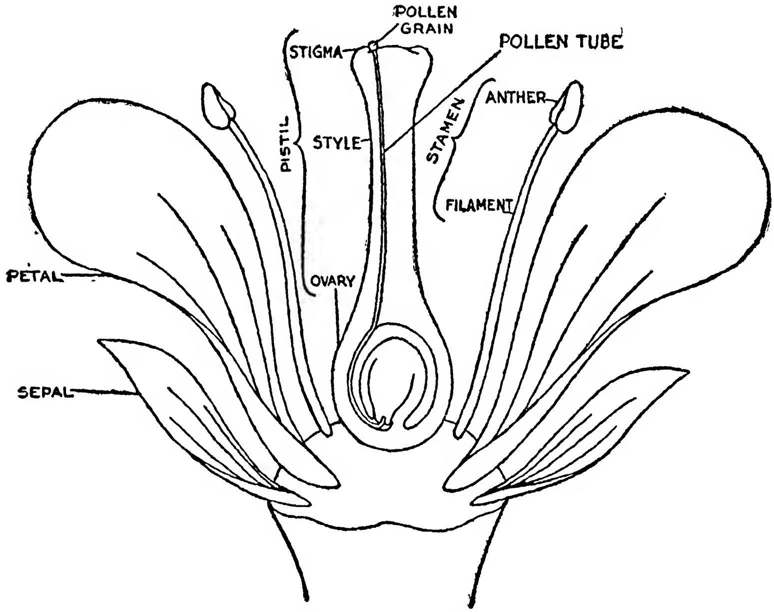


Fig. 39.—Diagram illustrating relation of floral parts. The pollen tube, which carries the sperms, is shown entering the "ovule." Within this ovule, female gametophyte and egg are carried. Fusion of sperm and egg will result in a zygote. This zygote will produce a young sporophyte, which will be imbedded within the ovule. By this time the ovule will have developed a tough wall, and be known as a seed.

The pollen grain is properly a spore and, like the spores of ancestral types, it produces a gametophyte. This gametophyte is so tiny, however, that it is contained entirely within the pollen grain. Here it produces its gametes, having a total output of just two sperms. Properly we may call this a male gametophyte, since it produces sperms and not eggs. The essential thing is that two sperms are carried inside each pollen grain.

Within the swollen base of the pistil, spores of a different type are carried. Each one produces a small gametophyte within its walls, and this is a female gametophyte, for it develops just one egg.

To effect fertilization it is necessary to convey the sperms, which are inside of the pollen grains, over to the eggs, which are well incarcerated in the base of the pistil. The journey is not accomplished by the swimming of the sperm; at last plants have become able to carry out the sex act in the absence of a water medium. Instead, it is the pollen grains that move. These are discharged from the stamen, and some are carried either by the wind or upon the bodies of insects to their proper destination. The insects are attracted to the flowers by the bright petals, and are rewarded by "nectar," which is secreted near the base of the petals. By these means some of the pollen grains are transferred to the top of the pistil. This may be either the pistil of the same flower, or of an entirely different flower.

On the top of the pistil is a sticky substance to which pollen grains adhere. At this point the pollen grains do a remarkable thing. Each one produces a tube which eats its way down into the pistil toward the eggs which are imbedded beneath. During this process, the two sperms, which were within the pollen grain, follow along at the tip of the tube. Finally the tube reaches the egg and discharges its sperms, one of which fertilizes the egg to form a zygote.

The zygote immediately starts to produce a young sporophyte, but simultaneously other changes are taking place in the surrounding tissue. These changes are of such a nature as to construct a hard wall, which completely surrounds the young sporophyte, and thereby checks its growth at an early stage. The resulting structure is a seed. It has a heavy coat, and, on the inside, an embryo sporophyte, and often some nutritive material to feed the sporophyte.

Seeds are thus produced inside the pistil. Later the pistil breaks, allowing the seeds to escape. Seeds are often endowed with wings or parachute attachments, so that they may be carried farther by the wind.

Normally seeds are distributed in the autumn and lie on the ground over winter, being protected by their heavy coats. The following spring, warm rains soften the seed coat, allowing the embryo to emerge, take root, and grow into the mature sporophyte.

Such is the rather involved life-cycle followed by all flowering plants. Details, of course, vary enormously. One or many seeds may be developed within a pistil. They may or may not be surrounded by the fleshy tissue we call fruit. One or many pistils may occur in a flower, and the other floral parts may vary enormously in size, shape, and adjustment to the visits of insects. In some plants stamens alone are contained in certain flowers, and only pistils in others. It may even be that stamens and pistils occur only upon separate sporophyte individuals. In the highest of all the seed plants, flowers become closely organized in groups, culminating in such a form as the dandelion, where numerous tiny flowers are compacted so closely together that we are likely to think of the entire group as a single flower.

In closing it is well to reiterate the general concept that the plant kingdom, from very humble beginnings, carried on a constant evolutionary advance, time after time adapting itself to new environmental situations, until, after a lapse of millions of years, it has conquered the land surface and produced the many highly-developed types that we see today. It is evidently the task of every group of organisms to produce higher, better groups by becoming adapted to its environment. The responsibility of the group is the responsibility of the individual; hence it becomes the task of every individual to adapt himself to the environment, to develop his own equipment for meeting the requirements of life. Later chapters will serve to clarify, as well as to amplify, this far-reaching biological principle.

SELECTED REFERENCES

1. John M. Coulter, *The Evolution of Sex in Plants* (University of Chicago Press, 1914).

2. R. M. Holman and W. W. Robbins, *A Textbook of General Botany* (New York: John Wiley and Sons, 1924).

3. G. M. Smith *et al*, *A Textbook of General Botany* (New York: Macmillan Co., 1924).

CHAPTER IX

INTERACTIONS BETWEEN PLANTS AND THEIR ENVIRONMENT

HENRY CHANDLER COWLES

I. The nature of the plant environment.—The effective environment of a plant consists of all the external factors which influence its structure and behavior. Among the more obvious of such factors are light, temperature, water, carbon dioxide, and oxygen. Also of great importance are the chemical and mechanical factors of the soil; nor must it be forgotten that plants are profoundly affected in their life and activity by other plants and by animals.

Careful observation and experiment show that some external factors are more important than others in determining the success of plants. Indeed, at times of stress the presence or absence of a single one of these factors may spell success or failure. Such a factor is termed a limiting or critical factor. Even in a group of a dozen factors all of which are fundamental, a single one often may be picked out as critical. For example, the presence of oxygen, carbon dioxide, nitrogen, and light is absolutely fundamental to the life of a green plant, yet another fundamental factor, namely, water, often is the critical factor, as in deserts, or in a period of drought in a climate that commonly is humid. Another factor that often is critical is temperature, as in a California lemon orchard in winter or on a Connecticut tobacco farm in early fall. Oxygen, nitrogen, carbon dioxide, and light much less commonly are limiting factors, because all of them usually are present in sufficient abundance for the needs of plants. In other words, tho fundamental factors are most likely to be critical which are mos variable and which are most likely to be wanting when needed. For each factor, too, there are points below or above which it is not effective. This is especially obvious in the case of temperature

where there is an easily demonstrated minimum below which and a maximum above which no life-processes take place. Somewhere in between these extremes are varying points that are best for the individual plant processes and also a point that is the optimum or best for the plant taken as a whole. It will be well now to consider one by one the chief external factors that influence plants.

a) *Light.*—Light in the form of solar energy may be thought of as the mainspring of all life, whether plant or animal, and as such may well be regarded as the most fundamental of all external factors. This is because light is necessary for the manufacture of carbohydrates, a process known as photosynthesis. This function of photosynthesis is a property of green plants, and will be described in a later paragraph. It is clear from the preceding that green plants cannot live permanently in the dark. During the night these plants cannot manufacture food except in the presence of artificial light. It is easily demonstrated that green plants can exist for some weeks or months in darkness, but no food can be manufactured there. Growth may take place in darkness, as in the sprouting of a potato in a dark cellar, but such growth is at the expense of food that was previously stored up. Plants behaving in this way decrease in weight and eventually die through lack of food. Some plants, such as mushrooms, can live through their entire life-cycle in the dark, but only when they are able to secure organic food previously stored up through the functioning of green plants which have been active in the sunlight. Plants and animals that live in the continual darkness of caves or of abysmal ocean depths are absolutely dependent for their food upon green plants active in the sunlight, however long and involved may be the chain of living forms between.

Light influences plants in other ways than through photosynthesis. One important effect of light is to increase the temperature of the plant. If the exposure to sunlight (insolation) is of too great duration or is too intense, plants are likely to suffer, not only directly through overheating but also through a greatly stimu-

lated loss of water. Light also has a profound influence upon growth, the exact nature of this influence varying widely with the species. In general, the tendency of a marked increase in light intensity or duration is to check growth and favor reproduction. However, recent studies show that in some cases reproduction is favored by a reduction of the insolation below that of normal daylight. It is probable indeed that each plant species has its own particular optimum of light for reproduction. Finally, light has a conspicuous influence on the distribution of plants. In deserts and in open exposed situations generally there grow plants that can tolerate or even may require intense illumination, while in the shade of the forests there grow much more tender and delicate plants that are quite unable to endure intense or extended insolation. A few minutes of direct sunlight may cause the leaves of these shade plants to wither, because such plants are unable to secure water from the soil fast enough to make good the loss by evaporation.

b) *Temperature.*—No factor more vividly than temperature illustrates the delicacy of the balance of the conditions that make life possible. Were the average temperatures a little greater or a little less than at present, were the summers a little hotter or the winters a little colder, life would become much more hazardous than it is. A marked change one way or the other would result in the death, first of the more sensitive of organisms, and eventually of all. When one contemplates the possible range of temperatures up and down, and still more the possible annual or seasonal fluctuations, it is easily realized how slender is the chance that any given world will have just the temperature conditions that make possible life as we know it. Geologic history shows that our earth has suffered pronounced temperature changes since life began. While many of these changes have resulted in a frightful slaughter of plants and animals, it is fortunate from our present point of view that species have the power to migrate and thus in large degree have been able to escape the rigors of unfavorable climates. From the point of view of life continuance, one of the

most fortunate circumstances of nature is the regular alternation of day and night. Continued insolation would through its cumulative effect soon result in temperatures that would be prohibitive of life.

The range of temperature for life-activities is very narrow, as compared with the range of possible temperatures.[1] Very few organisms are active at temperatures below 5° and these mostly plants and animals of arctic or alpine regions. Protoplasm is made up so largely of water that it is to be expected that activity would cease at the temperature when water freezes. A few marine organisms reproduce and vegetate at temperatures as low as −2°, because ocean water freezes below 0°. Many tropical plants only begin to be active at 10° or 15°. The varying response of plants to temperature is well shown by the germination of seeds. In such plants as lettuce, radish, wheat, and barley the seeds germinate readily at 10°–16°, whereas a temperature of 21°–27° is required for the effective germination of melons, corn, or pumpkins. It would also be expected that life-activities would cease at temperatures below 100°, the usual boiling-point of water at sea-level. As a matter of fact, life-activities cease much short of that, except in some blue-green algae and bacteria. Most plants are inactive at 45° or 50°, though there is a wide variation in this regard, depending on the species. Certain bacteria and blue-green algae are active in hot springs whose temperature is 80° or slightly more. The optimum temperature for organisms lies at some point between 0° and 45°, depending on the species. For the great majority of organisms the optimum temperature lies between 20° and 30°.

Organisms have a much greater range of endurance than of activity. This endurance range is especially evident for low temperatures. Many plants and most seeds and spores are able to survive the lowest temperatures that occur in nature. Indeed many seeds have been artificially subjected without the slightest injury to the lowest temperatures artificially obtainable. The re-

[1] The temperatures mentioned in this chapter are on the Centigrade scale.

sistance of organisms to high temperatures is much less. There is no wide range of capacity for dormancy above the temperatures that check activity. The most resistant of organisms are the blue-green algae and bacteria, which, as previously noted, are able to vegetate in hot springs at a temperature of 80°. The dormant stages of these plants are perhaps the most resistant forms of protoplasm, but even these are incapable of withstanding a temperature of 100° for any length of time.

Temperature is of great importance in determining within the limits of growth the rate of activity of most plant processes, such as photosynthesis, transpiration, absorption, and reproduction. For example, the absorption of water from the soil varies from zero slightly above the freezing-point of water to a maximum near the temperature of the growth optimum. This means that at high and low temperatures plants are likely to lose too much water by evaporation. The winter killing of wheat when not covered by snow is due mainly to the fact that evaporation losses cannot be made good by absorption on account of the low temperature. Similarly the injury or death of plants by overheating is due largely to their inability to absorb water fast enough to make good the unusually high loss.

Temperature is an outstanding factor in determining the distribution of plants over the surface of the earth. In the tropics grow those perennial plants that are intolerant of frost. In higher latitudes, except for certain annuals, there grow only those plants that are tolerant of frost. The deficiency of plants in polar climates, however, is due less to low temperatures than to the shortness of the season in which growth is possible.

Finally, temperature is of profound importance in agriculture. The crops that are grown by man in any given region are in large part determined by temperature relations. Frost-sensitive perennial crops, such as the banana, coconut, coffee, cacao, rubber trees, bamboo, are grown chiefly in the tropics. In warm temperate climates man grows many plants of tropical origin that are slightly cold-tolerant, such as the citrus fruits (oranges, lemons, grape

fruits, etc.), tea, and sugar cane, as well as such long-season annuals as rice, tobacco, and cotton. In colder climates are grown the hardier perennial crops, such as the apple and the strawberry, and short-season annuals, such as radishes, lettuce, and flax. In addition to these, some natural biennials, such as the beet and cabbage, are grown as annuals, since the part of the plant used in commerce develops the first season. Some frost-sensitive annuals, as the tomato and egg plant, acquire the length of season needed by a start indoors. On the whole, man's conquest of temperature is much less complete and satisfactory than his conquest of aridity. He has done a little in the citrus orchard by making smudges on frosty nights, but the radiation of heat from the earth's surface is so great that man's efforts in controlling it are puny. Man has done more, but still not much, in breeding cold-resistant varieties of plants, as in alfalfa, and by grafting tender desirable varieties on hardier stocks, as when the apple is grafted on the crab.

c) *Water.*—Water is much the largest component of active protoplasm, making up from 80 to 90 per cent of its weight, or even more. Protoplasm functions only when the cell has an ample supply of water. When the percentage in growing tissues is reduced, the activity of protoplasm is diminished, and a material reduction results in dormancy or even death. The change from activity to dormancy is well illustrated in seeds; a grain of wheat in the "milk" may have 48 per cent of its weight composed of water, but when ripe the amount may be as low as 13 per cent. Water is an essential raw material in the manufacture of plant food. Water as a solvent makes possible the absorption from the air and soil of all the materials that enter plants. Water serves as a medium of transportation of raw materials and foods within the plant. Water makes possible the maintenance of turgor in living cells. Water, by reason of its high specific heat, serves to reduce excessive overheating when plants are exposed to sunlight and high temperature. When with all these important properties of water we couple the fact that it usually is the most variable

in supply of all the important factors influencing plants, it is easy to see why students of plant science place such dominant emphasis upon it. It is more important as a limiting factor in plant life than all other factors put together.

One often speaks of the fitness of plants and animals to live in their environment. The environment must also be fit, and no other factor is more obviously fit than water. Among the many respects in which water is fit to be an environment for life as well as its major constituent, there may be noted here its unexampled solvent power, its great specific heat, and its capacity to expand on freezing. The solvent power has been already noted, as well as its high specific heat. In those two important respects no other substance could take the place of water. Water as the most perfect of solvents is the best fitted of all substances to dissolve the necessary constituents of plants and serve as a means by which they may enter and traverse plant bodies. The specific heat of water makes possible the preservation of relatively uniform temperature in plants, reducing both the heat effects of summer and the cold effects of winter. Aquatic organisms find here also one of their most salutary environmental relations, for the extremes of temperature changes characteristic of the air are greatly lessened in the water. Even the temperature changes of the air are made much less extreme by atmospheric moisture, as is evident especially in the neighborhood of oceans and lakes. The expansion of water when freezing means that ice floats instead of sinking, thus making possible the easy maintenance of aquatic life through winter under the ice. In conclusion on the fitness of water, it should be noted that water is fit chiefly when in a liquid state. It is unfit or inert when frozen and decidedly unfit when it is hot enough to vaporize through boiling.

Water is by far the most important of all factors in determining the distribution of plants over the surface of the earth. No greater contrast in plant life can be imagined than that existing between the tropical forests with their unparalleled luxuriance and the subtropical deserts with their poverty of vegetation. The

forms of plants in these contrasting places are also vastly different from each other. In the one place are tree ferns, bananas, and orchids; in the other are cacti and century plants. The three outstanding lowland landscape types of the earth are forests, prairies, and deserts, and their differences both in aspect and in component species are due almost wholly to differences in the water relations, especially rainfall and humidity. In quite as impressive a way water is responsible for most of the differences between the minor landscape types of any given region, such as swamps, meadows, and different kinds of woodland. These contrasts are due mainly to differences in the amount and depth of soil water.

In past geologic ages there have been profound differences in the distribution of water over the land surface of the earth. Mountains and bodies of water have appeared and disappeared. Areas now arid were once covered with forests and areas now covered with forests may one time have been arid. Some ages, such as the Pennsylvanian and Cretaceous, seem to have been more favorable for life than others, as the Permian. Differences in the water relations doubtless contributed largely to the differences in plant life. Fortunately, as with temperature changes, the ability of plants and animals to migrate has made survival possible.

Taken in the large, water is the most important factor that spells success or failure in agriculture. While temperature, as previously noted, is frequently a limiting factor, water is much oftener than temperature the factor of concern. Particularly serious is the fact that droughts with all their attendant evils may be expected at almost any time within the growing season, whereas the detrimental effects of temperature are much more closely tied up with certain seasons and hence can be more definitely anticipated and prepared for.

In view of the overwhelming importance of water in agriculture, and hence in the success of human life, it is fortunate that man's control of the water factor is much more complete than in the case of temperature. The arid regions of the west have been made largely arable through irrigation. The sagebrush deserts of

Utah and Washington, thanks to irrigation now "blossom as the rose," and in places land values have risen from almost nothing to $1,500 or $2,000 an acre. In areas of rainfall slightly below that necessary for normal crop production, crops may be grown by what is known as dry farming. This involves the principle of the conservation of water, which is actualized by fallowing in alternate seasons, surface mulching, and weed removal. Man also makes wet lands fit for agriculture by drainage. Hence, through water control, man is making the earth increasingly more habitable and more able to support an increased population.

d) Carbon dioxide.—When one contemplates the fundamental importance of carbon, making up as it does nearly half of the total dry weight of plants, and when one realizes that its source is the carbon dioxide of the atmosphere, he is almost appalled at its apparent scantiness. Only .03 per cent of the atmosphere is carbon dioxide; even the rare gas, argon, is more abundant. No other material factor fundamental to life is as rare as carbon dioxide, and yet so constant is its presence that it is rarely if ever a limiting factor for organic life, at least in the present geologic age. It is true, however, that vegetation increases in luxuriance when supplied with more carbon dioxide than is normal to the air. Green plants differ from other organisms in their ability to absorb carbon dioxide from the atmosphere and utilize it in the manufacture of carbohydrates, which then are used as food not only by the plants that made them but by all other organisms also. Thus the carbon abstracted from the air becomes locked up in the bodies of organisms. Some of the carbon thus locked up becomes released in respiration, which returns to the air once more as carbon dioxide. When the organisms die they are decomposed by bacteria and fungi, and again great quantities of carbon dioxide by this means are returned to the atmosphere. This rhythm of locking up and release of carbon is known as the carbon cycle. Much carbon is more permanently locked up in organic deposits, such as coal and limestone. It is believed that in past geologic ages the carbon dioxide of the atmosphere has fluctuated in

amount, some ages being characterized more by locking up and others by release. It is believed too that in those ages characterized by a relative excess of carbon dioxide, vegetation was more vigorous, partly because of more carbon available for food, and partly because of the greater uniformity of climate that was produced by the blanket-like effect of an excess of carbon dioxide in the air. The Pennsylvanian and Cretaceous ages may have been ages of this character, and the paucity of Permian vegetation may have been due in part to a deficiency of carbon dioxide with its twofold implication. In conclusion on carbon dioxide, it may be noted that carbon has a wonderful fitness for the part it plays. No other element is so rich in its almost infinite possibility of chemical combination and in the production of compounds of that degree of instability that fits them to play a proper part in the plastic phenomena of life.

e) *Oxygen.*—Oxygen, like carbon dioxide, is a fundamental factor that rarely is a limiting factor in plant life. The oxygen necessary for the building up of plant foods and plant structures is so much in excess in the water and carbon dioxide absorbed in connection with the function of photosynthesis that this process is characterized by the release of two atoms of oxygen into the air for every atom used. Since free oxygen makes up more than 20 per cent of the atmosphere, there is a very large excess beyond the needs of respiration. Only in a few situations in nature, as in swamps and in poorly aerated soils, is there a deficiency of oxygen for respiration. The stunted and horizontal roots of swamp plants are in part reactions to insufficient oxygen.

f) *Nitrogen.*—The most important constituent of protoplasm not yet mentioned is nitrogen. It is one of the oddities of nature that such an important element should enter plants through the roots, when four-fifths of the atmosphere is composed of nitrogen. Oxygen and carbon dioxide are acquired by plants largely from the air, as would be expected. Water and mineral salts are acquired largely from the soil, as would also be expected. Nitrogen alone, of the important plant constituents, is acquired in a round-

about way. Because of the inability of plants to utilize it in the free state, a nitrogen deficiency in the soil is often one of the most potent of limiting factors in crop production. Nitrogen is much less often a limiting factor in a state of nature than in agricultural lands, because, unlike man, nature does not remove her crops from the lands on which they grow, thus depleting the soil of some of its essential elements.

Plants build up their amino-acids and eventually their proteins for the most part from soil nitrates, and in much smaller part from ammonia and ammonium compounds. This process of protein synthesis, like the synthesis of carbohydrates, is a process carried on especially in leaves, so that in a double sense the leaves of green plants are about the most fundamental structures that there are in the world of organic life.

We may now contemplate briefly another of the fundamental processes of nature, namely, the way in which nitrogen becomes available for plants. The union of free nitrogen with some other element or elements is called nitrogen fixation. Through electric discharges in the atmosphere, small amounts of nitrogen oxides may be formed, after which they may enter the soil and combine with other substances to form nitrates. Vastly more important, however, in the matter of nitrogen fixation is the work of soil bacteria, such as Azotobacter and Clostridium, which build up nitrogen compounds in this manner, the necessary energy therefor being secured by the oxidation of carbon compounds in the soil. Another of the nitrogen-fixing bacteria is Pseudomonas, which performs this function either in the soil or in the roots of peas, beans, clover, alfalfa, and other members of the legume family. This family almost alone among all the higher plants has a fully satisfactory way of getting nitrogen, and the root bacteria are well off too, for they secure the carbon compounds necessary for their activity directly from the legume roots. Long before botanists knew of this reciprocal food relation between legumes and bacteria, practical farmers had discovered that one of the best ways of building up the nitrogen content of the soil was by grow-

ing legumes and plowing them under. There is yet another way by which the supply of available soil nitrogen may be increased. In the decomposition of proteins in the soil, ammonia is formed; this unites with other substances to form ammonium salts, which by further chemical action give rise to nitrates. The formation of nitrates in this manner is also a bacterial process, and is known as nitrification. There are two steps in this process, first the formation of nitrites by an organism known as Nitrosomonas, and second the formation of nitrates by another genus of bacteria, known as Nitrobacter. Unlike the nitrogen-fixing bacteria, these organisms are able to manufacture food from water and carbon dioxide and thus are comparable to green plants. In this activity too they are independent of the direct influence of sunlight, since they derive their energy by the oxidation of ammonium compounds and nitrates. However, even these remarkable bacteria depend eventually like all other organisms upon sunlight and photosynthesis, for the nitrogen compounds they employ are derived from dead organic matter. The complex chain of events above noted, viz., the fixation of nitrogen by such bacteria as Azotobacter, the utilization by green plants of the nitrates thus formed, the decomposition of organic matter, the formation of nitrites by Nitrosomonas, and the formation of nitrates by Nitrobacter, is known as the nitrogen cycle.

g) *Salts.*—In addition to the nitrogen salts previously described there are other soil salts that are essential to organic life, even though the total quantity involved is small. As with nitrogen salts there is rarely a deficiency of these other essential salts, except where man has removed them by continued cropping. One of the chief reasons for the use of fertilizers is to make good these artificially caused deficiencies. The hitherto unmentioned elements essential to life are phosphorus, sulphur, potassium, calcium, iron, boron, manganese, and magnesium. Plants contain other elements, essential in some cases, but not so generally as the foregoing. Man and other animals commonly secure the necessary mineral elements as well as their carbohydrates and proteins,

through the agency of plants. This seems to be almost necessarily the case with sulphur and phosphorus, but less so with the other elements. In addition to the salts that it contains, the soil is of great influence in plant life in the mechanical support that it affords to plants and in the protection that it gives to underground organs, but space will not permit their further consideration.

h) *Biotic factors.*—Plants are profoundly influenced in their life-activities by other plants and also by animals. Such influences are termed biotic or living factors, in contrast with those that have preceded. Such factors may influence plants for good or ill. They will be discussed more at length a little later on under the head of symbiosis.

II. The reactions of plants to their environment.—The activities of plants may be grouped under the headings of nutrition and reproduction. The nutritive or vegetative activities embrace the absorption of raw materials, the conduction of these materials to the seat of food manufacture, the manufacture of food, the conduction of the manufactured food to the various plant organs, the utilization of food, the storage of food excess, secretion, and excretion. The reproductive activities, which provide for the maintenance of the species, are vegetative reproduction, reproduction by non-sexual spores, and sex reproduction. These activities or functions usually are associated with special organs, as the root with the absorption of water, the leaf with food manufacture, and the flower with reproduction. In addition to the functions and structures just noted, mention should be made of protective functions and structures, such as the skin and the skeleton, which facilitate the maintenance of the other structures and activities of plants.

The space allotted does not permit a discussion of all the structures and functions of plants in their environmental relations. The reproductive structures and functions are here omitted except in the discussion of flowers, since they have been considered in the preceding chapter. The processes of metabolism common to organisms as a whole are discussed elsewhere. There may be singled out here two functions that are peculiarly well suited to

a discussion about plants in their environmental relations, viz., photosynthesis and transpiration. After the paragraphs devoted to transpiration, this chapter will conclude with a discussion of symbiosis, or the interrelations of organisms.

a) *Photosynthesis*.—The synthesis of carbohydrates from carbon dioxide and water through the agency of green plants in the presence of light is known as photosynthesis. It is the most fundamental process in all organic nature, for all life, both plant and animal, depends upon it. The water used in this process is derived usually from the soil, and the carbon dioxide is derived usually from the air. The light employed is sunlight, although artificial light can take its place; and as previously noted, the union of carbon dioxide and water can take place in the dark in certain bacteria. These exceptions are more apparent than real, however, since in each instance the sun is the ultimate source of energy. The particular part of the plant that carries on the work of photosynthesis is the part that is colored green. The green color in plant cells is due to a pigment known as chlorophyll which tinctures or suffuses small cell structures known as chloroplasts.

The water used in photosynthesis is absorbed from the soil by the roots and transported in the stem to the leaves in a specialized conductive system that is continuous throughout the plant. The carbon dioxide enters the leaf through pores, known as stomata, whence it passes into air chambers and eventually into the cells containing chlorophyll. The union of carbon dioxide and water results at first in the formation of a carbohydrate, the first obvious new compound being a sugar, such as glucose. The glucose molecule contains six atoms each of carbon and oxygen and twelve of hydrogen. If we imagine six molecules of carbon dioxide and six of water to unite to form glucose, it is obvious that there would be an excess of twelve atoms of oxygen, which escapes as waste. The escape of oxygen in photosynthesis can easily be seen in an aquarium containing green aquatic plants that are exposed to sunlight. From the sugars that are formed cellulose and fats may be produced, and eventually proteins when the necessary

additional elements become available. Often in strong sunlight a plant manufactures more sugar than it can immediately use or remove to other cells. Such sugar commonly is transformed to starch. Frequently an excess of starch accumulated by day is removed the following night.

Photosynthesis is facilitated by the behavior of leaves in relation to the sunlight. One of the commonest reactions in plant nature is the orientation of leaves with relation to light. When leaves are young and have the power of growth they tend to assume a position such that their surfaces will have an optimum amount of sunlight; in moderate light the optimum position is one in which the leaf surface has the maximum of illumination; in strong light the optimum position may be one in which the leaf has the minimum of light exposure. Thus in nature, shade leaves usually are oriented so that the leaf face is toward the light maximum, whereas in sun leaves the opposite is true. Once a definite leaf position is assumed the plant usually is unable to change it, even though it might be highly advantageous to do so. In a few plants, however, as in the nasturtium, plasticity remains for a long time.

Plants manufacture an amount of food that is greatly in excess of their own needs. Much of this excess is stored in tubers, bulbs, seeds, and other organs, and is used not by the plants themselves but by their progeny. This food excess of green plants is what makes life possible for us and for all other animals. But it is not alone for food that we are profoundly grateful for the process of photosynthesis in green plants. Photosynthesis makes possible our clothing, our furniture, and the wood we use in dwellings, and other human structures. It makes possible the wood we use in boxes, and tools, and the wood we use to burn. Photosynthesis in former ages made possible our coal and our petroleum on which modern civilization is so largely based. Perhaps the day may come when the chemist as well as the plant may effectively synthesize water and carbon dioxide and thus abolish agriculture, and make the use of plants a memory. At any rate in all the past and per-

haps for some time yet to come, green plants may be thought of as the most important chemical laboratories that the world affords.

b) *The water relations of plants.*—Since water is commonly the most important limiting factor in plant life, it might be expected that in the process of evolution the most successful plants would be those that happen to have advantageous ways of getting or retaining it. In land plants, as previously noted, roots are the chief organs of water absorption. Not all of the root is involved in this, but only the region of the tip with its delicate specialized root hairs. The water enters the root, and from the outer root cells it enters the conductive tract and ascends to the leaves. The mechanism of this conduction is not wholly understood, and somewhat too complicated to discuss here. In submersed water plants the mechanism for getting water is much simpler than in land plants, the leaves having the ability to absorb water as well as carbon dioxide from the surrounding medium, thus obviating the necessity of transportation. In desert soils one finds two sharply contrasting types of root systems, some plants such as cacti having shallow spreading roots that absorb rain water, whereas other species of plants have roots that extend to deep subterranean water sources. Some people have looked for specialized absorptive organs on the leaves and stems of desert plants. Such absorptive organs have not been discovered, nor indeed are they to be expected, inasmuch as an organ that would take water in would also let it out; and in an arid climate there are many more days when water would go out from a leaf than there are days when water could enter. Organs for aerial water absorption are found, however, in mosses and lichens. Mosses largely grow in moist woods where water is usually available, but some mosses and most lichens grow in very arid situations. The only statement we can make concerning this is that these lowly plants are in some way able to dry out and become dormant without suffering harm.

The most interesting and diversified water relation of plants is in connection with transpiration, which may be defined as evaporation of water from plant surfaces. The amount of water

lost in this way by plants is indeed stupendous. An ordinary sunflower plant on a hot summer day may lose two pounds of water and a beech tree may lose as much as two barrels. It can be well imagined that the daily loss from a wheat field or a woodland would mount up into many tons. Much thought has been given by botanists to the significance of transpiration. Some have thought of it as a necessary evil. That it is necessary is clear enough, for one cannot picture a non-transpiring leaf. It is necessary for a leaf to be permeable or porous to carbon dioxide, so that photosynthesis can go on. And one cannot imagine a leaf so constructed as to let carbon dioxide in without letting water out. Transpiration, however, is not wholly an evil. It prevents the overheating of leaves. It makes possible the rapid conduction of water in stems and doubtless facilitates the upward movement of soil salts. And yet transpiration is a very dangerous thing for plants, perhaps the most dangerous thing there is.

There are many ways in which the loss of water from plant surfaces is lessened, but only a limited tabulation may here be made of the more important. The stomata of most plants close at night, thus cutting off the loss of water when there is no photosynthesis. Stomata close also in dry weather; this greatly lessens photosynthesis, but obviously it is more desirable that food-making should cease than that the plant should suffer through loss of water. Plants often shed their leaves, not only at the approach of a cold season, but also at the inception of drought; in either case evaporation is greatly lessened. There are many plant structures that reduce transpiration, such as the cutinized layers in the skins of leaves and the corky layers in the bark of trees. The dwarfing of plants and their growth in compact cushions also bring about a lessened loss of water. In many plants, as in cacti, the dangers of excessive transpiration are in large part obviated by the accumulation of water in great excess in some of the plant organs. The accumulation of great supplies of water in underground organs is particularly effective, because such organs are essentially free from losses by transpiration. In spite of all these

and many other forms of structure and behavior that reduce or make up for evaporation, plants are still far from adequately provided with means of checking water loss. In nature as in agriculture drought is one of the greatest dangers to which plants ever are exposed.

c) *Symbiosis.*—When two or more organisms live together in more or less intimate relationship, the phenomenon is termed symbiosis and the individual organisms are termed symbionts. If the relationship is beneficial to both symbionts, the phenomenon is known as mutualism; a good illustration of mutualistic symbiosis is shown in the relation between clovers and their root bacteria, previously described. More frequently, perhaps, one of the symbionts is benefited and the other harmed; this is known as antagonistic symbiosis and is well illustrated by parasitism, where one organism, known as the parasite, secures food or food materials from another, known as the host. Mistletoe is a well-known parasite of trees in the southern states. Its leaves are green, which would indicate that the plant manufactures its own food. It derives carbon dioxide from the air like other green plants, but it draws its water from the tree on which it grows, instead of from the soil, hence is known as a water parasite. Dodder, a rather common twining parasite of yellow or orange color, is without chlorophyll and derives its sugar from the host plant. Some parasites derive proteins as well as carbohydrates from their hosts. Not all plants without chlorophyll are parasites. The indian pipe, a well-known summer plant of rich woods, gets its food from dead organic matter. Such a plant is called a saprophyte. The fungi and bacteria are either saprophytes or parasites, and there are some species that can derive their food from either living or dead matter.

One of the most extraordinary cases of mutualistic symbiosis is illustrated in the relations existing between flowers and insects. For flowers to produce fertile seeds it is necessary that pollen grains be transferred from the stamens to the stigma, which is the sticky receptive surface at the apex of the pistil (Fig. 39, p. 237).

These pollen grains germinate on the stigma, developing pollen tubes which carry the sperms down to the eggs at the base of the pistil. Fertilization here takes place and the seeds develop. Flowers are so constructed that it is usually difficult for pollen by itself to drop on the stigma. Some agent commonly is necessary to bring about the pollen transfer, a process known as pollination. In many flowers with conspicuously exposed stamens and stigma, such as corn, wind is the agent of pollination. In many other flowers, perhaps in the majority, the pollinating agents are insects. The insect-pollinated flowers usually are showy or odoriferous or both, and usually they secrete nectar, for which the insects visit the flowers. In the search for nectar the insects come in contact with the stigmas and stamens and necessarily rub off pollen on the sticky stigmatic surfaces. Much the most efficient of all pollinating insects are the bees, and many flowers are so constructed that bees can readily secure nectar from them, whereas insects without long mouth parts may search in vain for the desired reward. Flowers which in structure are notoriously related to bees are clover and other legumes, the snapdragon, and many orchids.

One of the noteworthy discoveries made by Darwin was that cross-pollination, or the transfer of pollen from one plant to another, usually is better than close-pollination, or transfer within the same plant. Indeed, many plants are sterile to their own pollen and produce seed only when pollen transfer is effected from another plant. Self-sterility of this sort is seen in clover, rye, and in many apples, pears, and cherries. On the other hand, a number of plants, such as wheat, oats, tobacco, and cotton, are self-fertile. An intermediate situation is illustrated by corn, which while self-fertile, produces a much better crop if cross-pollinated.

One of the great discoveries of our own day is the self-sterility of many of our best varieties of apples, pears, and cherries. The fruit growers of the west a few years ago became alarmed at the gradual deterioration of their crop. They sought the explanation in changes of one sort or another in the soil or climate; they looked

for an explanation in insect and fungus pests. But all these studies proved in vain. Finally it was discovered that to have apples one must have apple seeds; to have apple seeds, one must have pollen transfer and fertilization; to have pollen transfer one must have bees. And most important of all one must not have just one kind of apple, for most apples are sterile to their own pollen. Pollen transfer from one Jonathan apple tree to another is not cross-pollination, for since these trees are propagated by grafting and not by seed every Jonathan apple tree is really a branch of the original Jonathan apple tree. In a very real sense there is only one Jonathan apple tree in all the world! The reason why this tremendously important discovery of the necessity for cross-pollination was not made long ago is because eastern apple growers usually had several varieties of apple in their orchards; furthermore many of the old varieties of the apple, like the Baldwin, are perfectly self-fertile. In modern apple culture it is found that some varieties are better for cross-pollination than others—these are known as congenial varieties. The successful grower of today interplants the desired variety with a congenial variety and in addition he keeps bees so that optimum cross-pollination may take place.

As a final thought in this chapter attention may be called to the fact that all organic nature is a vast and complicated symbiosis. While the green plant is the most independent of all organisms, it depends much on other organisms. For its nitrogen it depends on the bacteria. For its pollination it may depend on insects. Some of its food it may get from dead organic matter instead of making it anew. In a hundred other ways its life is affected by other plants and animals. In the animal world this symbiotic relationship is even more pronounced, because animals are devoid of chlorophyll, and hence necessarily dependent. While the first forms of life must have been altogether independent it is obvious that evolution has resulted in the general interdependence of organisms, a universal symbiosis.

SELECTED REFERENCES

For selected references, see chapter viii.

CHAPTER X

THE EVOLUTION OF THE INVERTEBRATES

W. C. ALLEE

The invertebrates are the animals that lack a vertebral column, or backbone. They are widespread and abundant both in species and in individuals. One sees representative invertebrates in a drop of apparently clear pond water when inspected through a microscope; within its narrow bounds they frequently swim in dense swarms. They make the profuse flower-like growths of tide-pools or "marine gardens." They are nowhere more numerous than in the tropics, where mosquitoes, ticks, mites, termites, and ants overrun forest and village. But even in arid regions they comprise the majority of the animal species and are the main pests against which man struggles for a living. Minute invertebrates may be so numerous in the ocean that they discolor it for miles and by their abundance affect it profoundly. The bottom of much of the sea is composed of the shells and skeletons of invertebrates. They are directly responsible for the formation of great banks of limestone; and one small group alone, the coral polyp, has added thousands of square miles to the land surface of the earth.

Not all invertebrate animals are free-living. In fact, practically all of the animal parasites attacking man and the other animals are invertebrates. A drop of blood from a person suffering with African sleeping sickness, malaria, or syphilis, swarms with minute invertebrate parasites. The hookworm infests many people of all social classes in the warmer parts of the earth, extending as far north in the United States as Arkansas and Virginia; by decreasing the energy and resistance of its victims it has helped retard the development of some of the most fertile lands of the earth. Lice, fleas, bedbugs, mosquitoes, leeches, chiggers, tape-

worms, and some two hundred more are known to live in man's body or to obtain their food from his blood.

These parasitic invertebrates are loathsome to most people; but even the casual observer, when shown delicately beautiful jellyfish, sparkling fireflies, brilliantly hued butterflies and beetles, marvelous corals, and active squid, whose vivid colors change with every movement, is convinced that beauty has not been developed among the vertebrates alone.

Invertebrates make up the bulk of the animal kingdom. In round numbers, there are some 600,000 recorded species of living invertebrates and only 36,000 known species of vertebrates. Something of the abundance of the invertebrates may be realized when one finds that the insects alone, which constitute only one class of one phylum (as the larger divisions of the animal kingdom are called) include three-fourths of all described species of animals. The other fourth includes the rest of the invertebrates and the relatively few vertebrates as well. The vertebrate group does not even compose all of one phylum of animals, but is one of four subphyla of the phylum Chordata.

Thus, in dealing with the evolution of the invertebrates we are studying the evolution of the overwhelming majority of animals. The principles involved here are the same as those in the evolution of the vertebrates to be traced later, and it is largely lack of space which prevents the detailed treatment of invertebrate animals that may be given in studying the evolution of the much more compact vertebrate group.

The question of the course of evolution of the animal kingdom attracted much attention from investigators during the third of a century that followed Darwin's announcement of a logical theory to account for evolution. In recent years the discussion of ancestries has lagged among scientists, not because the problems are solved, but with the main outlines sketched and with obvious relationships discovered, the attention of research workers has turned to fields offering more definite results for the same amount of labor.

In entering this field it is necessary to remember that in many cases the relationships suggested cannot be proved, and that there are views dissenting from those here presented. The outline hastily sketched in this chapter may serve as a background of fact and theory against which the development and activities of the vertebrates in general, and of man in particular, may intelligently be viewed. It should also serve as a convenient skeleton to be filled out later as the reader's information accumulates.

Principles of classification.—To talk intelligently about the evolution of invertebrates we must get some orderly arrangement in which we can view them and so understand the general principles marking their affinities. Men have long been engaged on the problems of correct classification of these groups and have labored to arrange them in series depending on natural relationships rather than on superficial similarities. For this purpose they have used such criteria as the following:

Do the animals when adult have one or more cells? Are they radially or bilaterally symmetrical; or do they lack symmetry? Does the alimentary canal have one or two openings? What is the architectural plan of the nervous system and of other systems of body organs, especially of those dealing with waste products and with reproduction? Do chemical tests of the blood show signs of relationships?

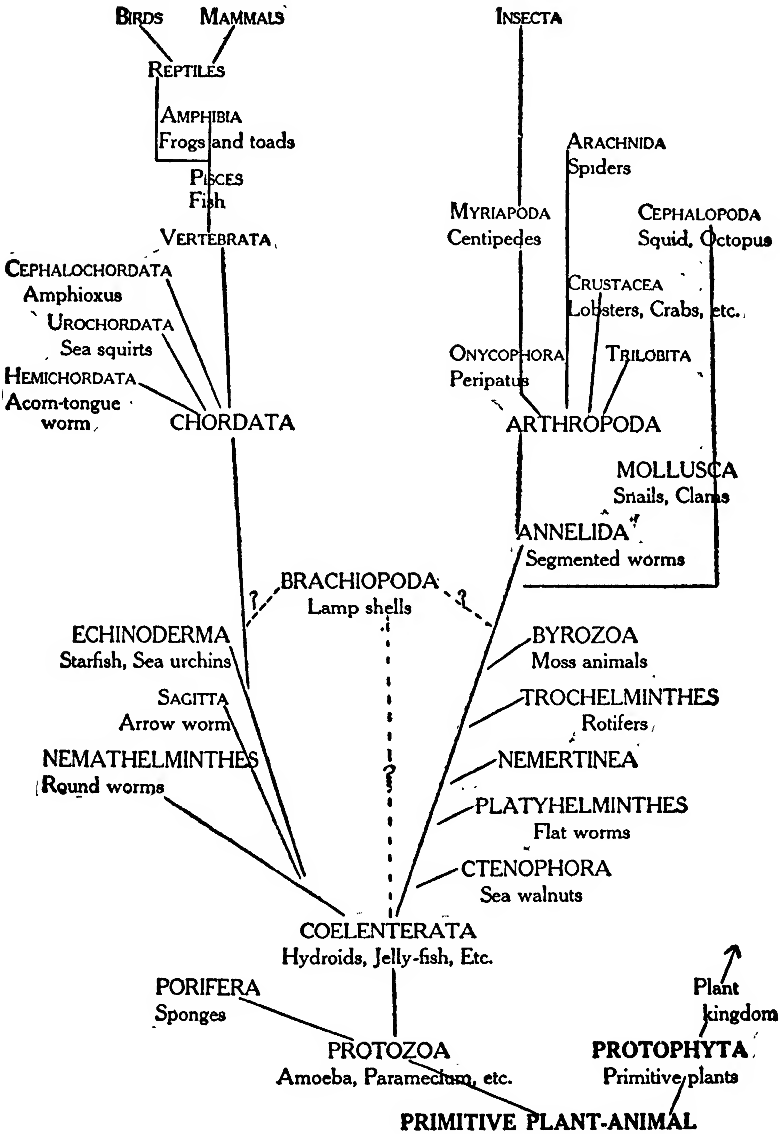
With embryos they ask:

What is the type of division after fertilization? How are the different embryonic stages formed? How many sheets of embryonic cells, called germ-layers, are developed? What is the method of formation of the coelom, or body cavity? What resemblance has the developing embryo to other embryos and to the adults of other animals?

By such comparisons and distinctions the animal kingdom has been divided first into subkingdoms, then into phyla, classes, orders, families, genera, and species, always on the basis of the relationships of the different groups in so far as they could be

CHART I

RELATIONSHIPS OF THE ANIMAL KINGDOM



discovered. One view of the relations of the phyla and of some of their classes is shown in Chart I (p. 263).[1]

An invertebrate who's who.—The array of names in the chart will be meaningless without explanation. Beginning at the bottom, the **Primitive plant-animals** are a poorly defined group of organisms, usually with a single cell, and even when best developed, lacking tissues. They are usually green, possessing chlorophyll (although some lack this), and microscopic, though here again

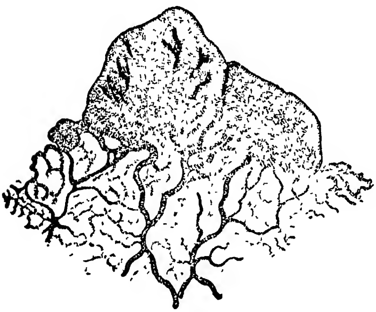


FIG. 40.—A part of the body of one of the slime molds. (After Lister.)

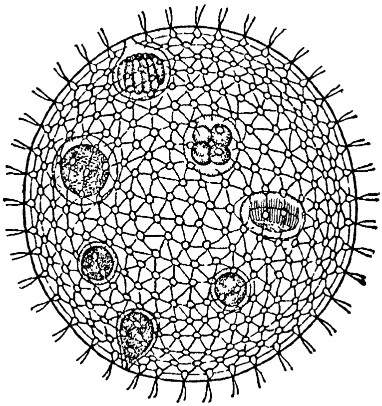


FIG. 41.—*Volvox*, a complex plantlike protozoan colony. (After Leuckart.)

there are notable exceptions. They combine plant and animal characteristics to such an extent that they are claimed by both botanists and zoölogists. There is no distinct line that can be drawn between them and either plants or animals. They are closely related to the PROTOPHYTA, which are the simplest plants, and to the PROTOZOA, the simplest animals. Through the former they are connected with all the plant kingdom, as indicated by the lines at the extreme lower right of the chart. Slime molds,

[1] This chart was originally worked out from suggestions received indirectly from Professor E. B. Wilson. It has been checked with the phylogenetic data given in MacBride, *Text-Book of Embryology*, Vol. I, and has been criticized by Dr. R. H. Bowen and Dr. B. H. Willier.

Euglena, and Volvox, may be given as common examples of this informal group of organisms.

The Phylum PROTOZOA (*primitive animals:* Amoeba [Fig. 42], Paramecium [Fig. 43], etc.) consists of minute animals without tissues, usually said to be composed of a single cell and almost always microscopic in size. There are some 8,500 known species

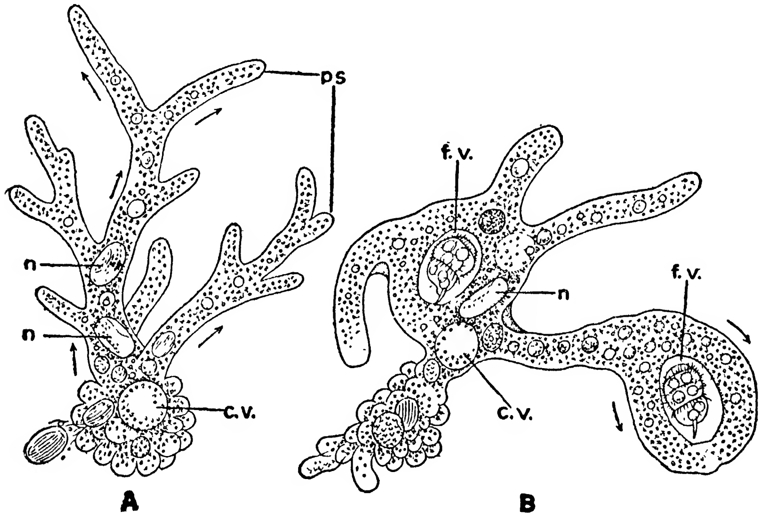


FIG. 42.—Two views of *Amoeba,* one of the relatively simple protozoans, showing two of the various forms assumed by this species. *ps,* pseudopodia; *fv,* food vacuole; *n,* nucleus; *cv,* contractile vacuole. (From Newman, after Leidy.)

grouped in four classes. They live in the ocean, in fresh water, in the soil, and as parasites in both plants and animals.

Animals from this phylum cause malaria, syphilis, African sleeping sickness, oriental sores, dum-dum fever of India, amoebic dysentery, a severe intestinal disturbance caused by Amoeba from impure drinking water, and perhaps smallpox, hydrophobia, and yellow fever. Many of these diseases cause severe epidemics and for this reason the study of Protozoa is coming to rank close to that of bacteria in medical science.

Protozoa have undergone an evolution that has produced some

remarkably complex animals which, while still protozoans, are far removed from their simpler living relatives, and these in turn

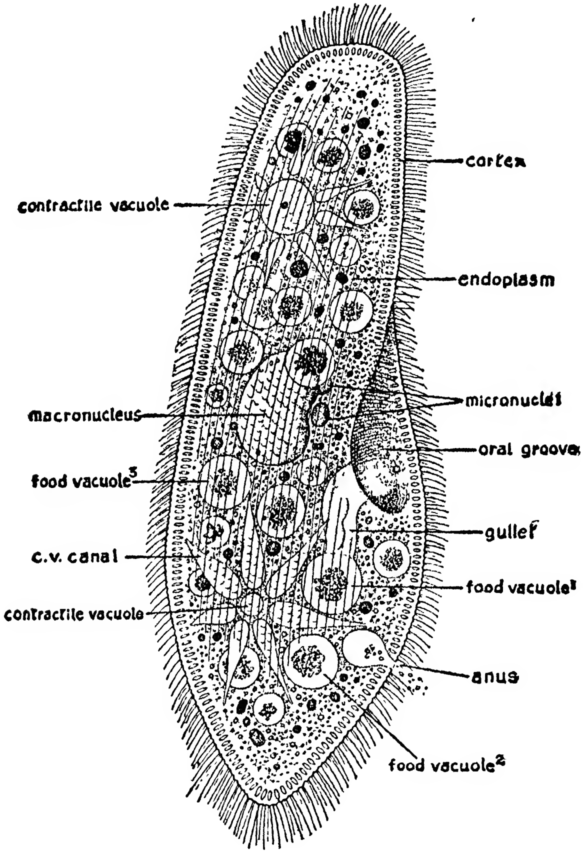


FIG. 43.—*Paramecium,* one of the more specialized protozoans. (From Newman, after Pfürtscheller wall chart.)

must be very unlike the first Protozoa. This evolution has taken place in separate cells which live as independent units.

In some Protozoa, small colonies of cells are formed as are shown in Figure 44, but even in these colonial protozoans there is no development of specialized cells joined into tissues such as

occur in the next step of evolution. From evidence to be presented later, we assume that the primitive ocean was first populated with free-swimming one-celled animals which later developed into small colonies, and finally into globular colonies something like Volvox is today, except for the chlorophyll. They were like the modern free-swimming blastula stage present in the early development of many animals. These spread through all the waters of the early earth and came to occupy all available habitats.

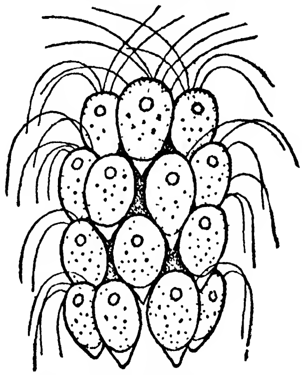


FIG. 44.—A simple plantlike protozoan colony. (After Conn.)

One group of such free-swimming colonies became bottom feeders and developed into the modern phylum PORIFERA (*pore bearers:* sponges). These are plantlike, fixed, aquatic, animals with the body wall perforated by many pores. They may have radial symmetry or be asymmetrical. The sponges number about 2,500 species, mostly marine, but with one small group in fresh water.

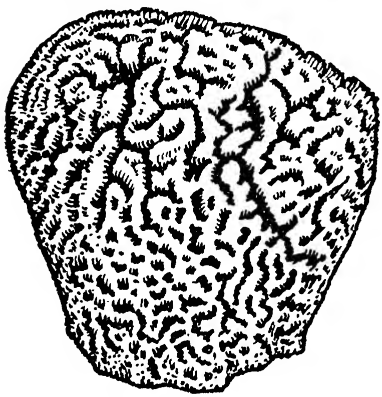


FIG. 45.—A bath sponge. (After Hyatt.)

Sponges are loosely organized animals. They may be cut into small bits and the pieces strained through a fine meshed silk cloth until they are separated into single cells; yet these cells will come together in small clumps capable of growing into new sponges.

The sponge line of development ends blindly. It is to be regarded as a low side branch from the trunk of the ancestral tree of the animal kingdom. We are more interested in the main stem which is represented by the development of the free-swimming,

hollow, blastula-like ancestral form into the phylum we now know as the COELENTERATA (*coelom and gut combined:* hydroids, jellyfishes, corals, sea anemones, etc.).

The coelenterates are radially symmetrical animals with two germ layers, tentacles, stinging cells, and a single internal cavity opening to the outside through but one passage, the mouth. There are two main body forms, the plant-like hydroid and the jellyfish-

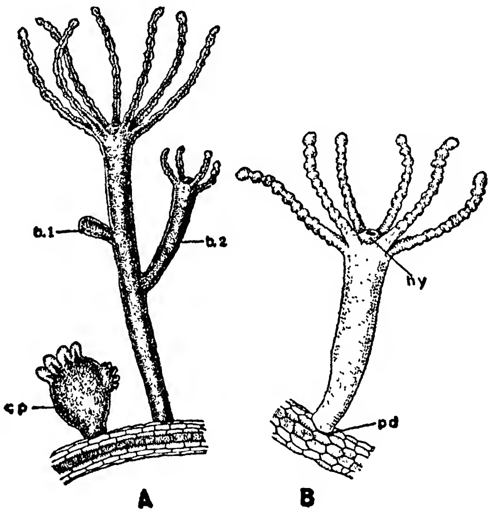


FIG. 46.—*Hydra*, a relatively simple hydroid coelenterate. *B* shows an unbranched typical individual. In *A*, two buds are shown which in time will separate to form new individuals. *cp*, concentrated condition; *hy*, the mouth region; *pd*, the foot. (From Newman, after a Pfürtscheller wall chart.)

like medusoid. The three classes contain about 4,200 species, largely marine, but with a few fresh-water representatives of which the hydra is best known.

What occurred to produce the coelenterate from protozoan stock? Apparently the free-swimming Volvox-like ancestor of the coelenterates with a single layer of ciliated cells over the outer surface became converted into a two-layered structure with an opening at the posterior end (a gastrula; see Fig. 75). This came about through an infolding of the hinder half of the ball where the cells

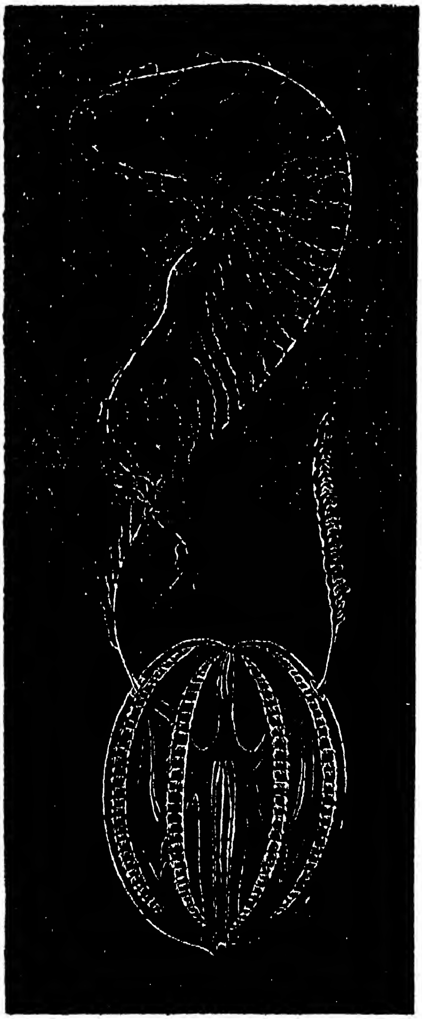


FIG. 48.—*Pleurobrachia,* one of the ctenophores which illustrates why the group is sometimes spoken of as the sea walnuts. (After Mayer.)

had specialized in gathering the small food particles that tended to collect in the wake of the free-swimming animal. When the free-moving animal settled head first against a rock, it formed a more or less permanent attachment and underwent a reversal in organization; the old posterior opening became a mouth. At least something like this happens when the free-swimming larvae of some of the present-day coelenterates swim head first against a rock and settle there.

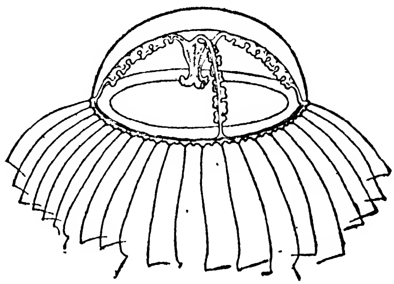


FIG. 47.—*Gonionemus*, a jellyfish. (After Mayer.)

From the Coelenterata two distinct types of organisms developed into the two great branches of the animal kingdom. The fundamental differences between these two main trunks will be shown later. For the present we shall call the line to the right, the ARTHROPOD series, and that to the left, the CHORDATE series, on the basis of their most highly developed members. All the phyla of both series have three germ layers.

The arthropod series.—Some of the free-swimming coelenterate ancestors never settled to the bottom; these gave rise to the freely moving phylum CTENOPHORA (*comb bearers:* sea walnuts). The ctenophores are medusa-like animals, but sufficiently progressed to have two openings to the digestive tract, as well as both radial and bilateral symmetry. They bear eight rows of comblike swimming plates made of fused cilia (Fig. 48). They constitute a small phylum of 100 marine species in two classes.

The modern representatives of this ancient group are clear jelly-like animals, many of them composed of water to about 95 per cent of their total weight. They may be broken to pieces by the splash of an oar or the breaking of a wave, so that if the sea is disturbed they are safe only when they swim down into the quiet

water below the waves. On quiet days in regions where ctenophores are abundant, a bucket dipped into the sea may bring up more of these fragile sea walnuts than of water.

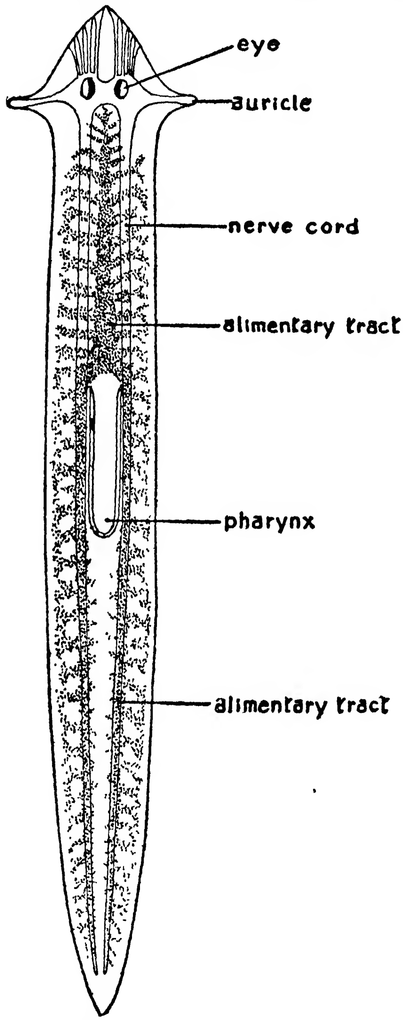


FIG. 49.—*Planaria*, one of the free-living flatworms of the Phylum Platyhelminthes. (From Newman, after Child.)

Some of the ancestral ctenophore-like animals settled to the bottom at various stages in their evolution and gave rise to the different members of the great group of wormlike animals which are now divided into a number of phyla, and to the snail-shellfish group which we know as molluscs. These are given in the order of their degree of specialization.

Phylum PLATYHELMINTHES (*flatworms:* Planarians, liver flukes, and tapeworms). These are soft-bodied, unsegmented, flattened, bilaterally symmetrical animals with a digestive cavity that opens to the outside only through the mouth. There is no real body cavity between the intestine and the skin. In extreme parasitic forms, the entire digestive cavity is lacking. There are 4,600 species in three classes, two of which are mainly parasitic. The others are, for the most part, marine and fresh-water animals.

Both of the parasitic classes, the liver flukes and the tapeworms, attack man as well as the other vertebrate animals. They may be present in a single individual in remarkably large numbers; the intestine of a single dogfish may contain enough tapeworms to supply a class of 200 students with laboratory material.

Phylum NEMERTINIA (*unerring aim:* Cerebratulus, Lineus). This is a small group of 400 species that are mainly marine and closely resemble the flatworms. They have, however, a proboscis lying just above the alimentary canal that can be thrown out and retracted; and they have also an anus, or posterior opening to the intestine. These worms have great powers of extension and contraction. A plump worm a few feet long may expand into a graceful free-swimming ribbon-like animal 90 feet or more in length. Many of them, however, are quite tiny. The one most commonly found on wharf pilings along the New England coast is about a half-inch long.

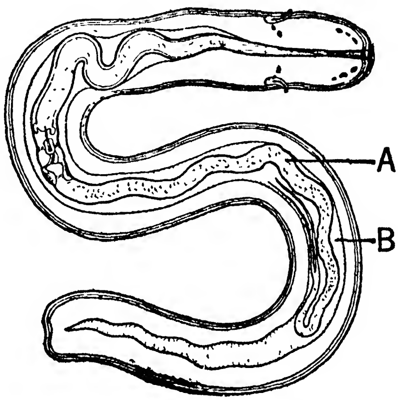


FIG. 50.—A nemertian. The prominent proboscis (*A*) is shown lying above the alimentary canal (*B*). (After Leuckart and Nitsche.)

Phylum TROCHELMINTHES (*wheel worms:* rotifers, wheel animalcules). These are microscopic aquatic animals with the body divided into the head, which is a ciliated disc; the trunk, which may bear a shell; and the tail or foot which bears a cement gland by means of which the animal fastens itself to the substratum. There are about 900 species in three classes, almost all found in fresh water.

Rotifers are capable of withstanding drying and one of the best places to collect many sorts is in the débris that gathers in

the bottom of dry urns in cemeteries. They become active again when the urns fill with rain water. Rotifers can also withstand continued freezing and occur in the Antarctic lakes that are solid ice except for a brief summer period when a surface layer melts and the contained rotifers become active. The general resemblance of rotifers and certain free-swimming marine larvae will be discussed later.

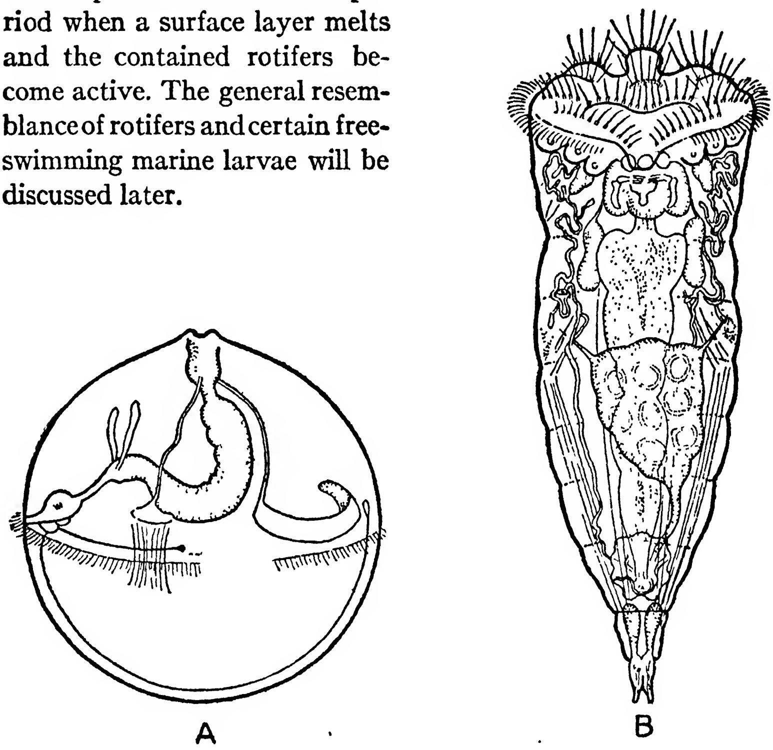


FIG. 51.—Two rotifers. In (*A*) the cilia are located approximately as in the trochophore larvae (Fig. 38). In (*B*) they are found only as a complicated crown on the upper (anterior) end. (After Hudson.)

Phylum BRYOZOA (*moss animals*, called also POLYZOA, *multiple animals:* Bugula, Plumatella, etc.). These are small, usually colonial animals, superficially resembling hydroids, but with three germ layers, ciliated tentacles, a coelom, and with two openings to the U-shaped alimentary canal. There are about 1,750 species in two classes, mainly marine.

These animals have never developed an adequate excretory system. In this they have lagged behind the last three phyla. When waste products accumulate too greatly, and perhaps for other reasons, the animal ceases activity and forms a rounded ball-like cyst called a "brown body." Inside this brown body reconstruction processes take place and at length a rejuvenated animal emerges with the old waste material inside the new intestine from which it can be ejected. The bryozoans are a very ancient group which have been living since early Paleozoic times.

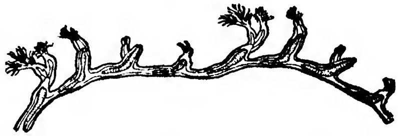


FIG. 52.—*Plumatella*, a fresh-water bryozoan. (After Davenport.)

Phylum BRACHIOPODA (*arm footed:* lamp shells). These are sessile, mollusc-like animals with the body enclosed in a shell composed of unequal dorsal and ventral valves. Long ciliated arms are their most conspicuous body organs. There are about 120 living and 2,500 fossil species, all marine. The phylum contains LINGULA, the oldest living genus of animals, which is known from the rocks of the lower Cambrian (see Table I, p. 84). At present the brachiopods are but a lingering relic of a group once abundant and widely distributed. They may belong in the chordate rather than in the arthropod series, but this point will be discussed later.

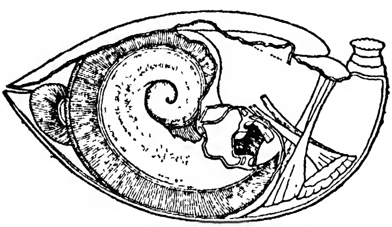


FIG. 53.—A brachiopod dissected to show the coiled ciliated arms; note also the unequal dorsal and ventral valves. (Modified from Leuckart.)

Phylum ANNELIDA (*ringed:* earthworms, leeches, clam worms, etc.). These are elongated, wormlike animals with the body plainly and completely segmented. They have a well-developed coelom and their blood flows through closed tubes such as occur in vertebrates. They also have tubular excretory structures which resemble the first form of kidneys to be found

in the vertebrate embryos. There are about 4,500 species in four classes. They are found in the sea, fresh water, and on land. These

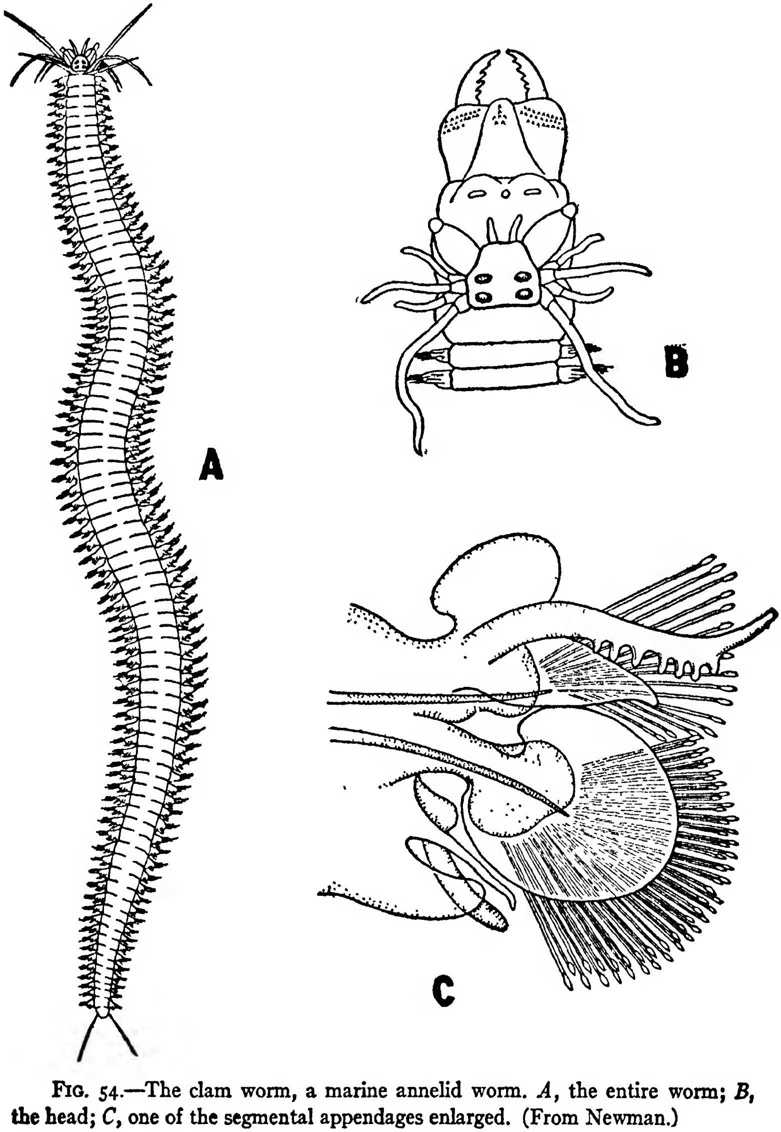


Fig. 54.—The clam worm, a marine annelid worm. *A*, the entire worm; *B*, the head; *C*, one of the segmental appendages enlarged. (From Newman.)

are the typical animals just as the ferns are the median plants. If one were to be limited to studying a single representative of all the animal kingdom, he had best choose an annelid worm. But earthworms are of much more importance to man than merely as convenient laboratory representatives of this median phylum. Pasteur found that they bring up disease germs from the bodies of buried animals and so start epidemics. Charles Darwin busied himself with their general activities and concludes his readable booklet on *Vegetable Mould and Earthworms* as follows:

> When we behold a wide, turf-covered expanse, we should remember that its smoothness on which so much of its beauty depends, is mainly due to all the inequalities having been slowly leveled by worms. It is a marvelous reflection that the whole of the superficial mould has passed and will pass, every few years, through the bodies of worms. The plough is one of man's oldest inventions; but long before he existed the land was in fact regularly ploughed by earthworms. It may be doubted whether there are many other animals which have played so important a part in the history of the world as have these lowly organized creatures.

Phylum MOLLUSCA (*soft body:* snails, mussels, clams, oysters, squid, etc.). Molluscs are bilaterally symmetrical or spirally coiled, unsegmented animals, whose body is usually covered with a calcareous shell and is composed of four parts, the head, the mantle, the foot, and the body mass. Molluscs are divided into five classes with 60,000 living species, marine, fresh water, and land.

The molluscs are of interest to laymen in zoölogy because of their ability, widespread in the group, to produce image-forming eyes, resembling our own in general structure. Even the bivalved shellfish (a group including the succulent oyster and the tough mussel, both eyeless) have actively swimming representatives called scallops, possessing a row of eyes along each free margin of the mantle; and they look up at you with from one to ten dozen pairs of these cold, unblinking eyes.

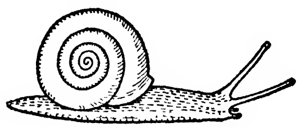


FIG. 55.—A land snail. (From Baker after Binney.)

The bivalve molluscs furnish us with pearls and with the so-called pearl buttons as well as food, and some of their number do civilization notable injury. The "shipworm" (a mollusc) burrows into wood that is exposed to sea water, causing wooden vessels to become rotten and wharfs to collapse. In San Francisco Bay in 1920–21 about $20,000,000 was spent in replacing pilings weakened or broken because of these worms.

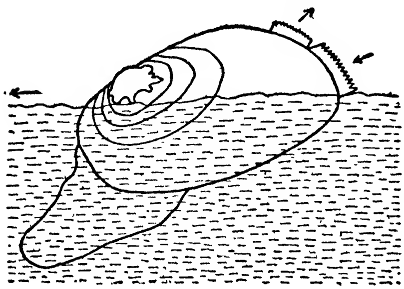


FIG. 56.—A fresh-water mussel in natural position. The animal is represented moving toward the left with its foot and the lower part of the shell buried in the stream-bed. The arrows at the posterior end show the direction of the water currents from which the animal obtains food and oxygen. (From Baker, after Morse.)

The class CEPHALOPODA (*head footed:* squid and devilfish) consists of molluscs frequently lacking a calcareous shell. They have a large head bearing well-developed eyes and there is a circle of tentacles about the mouth, usually supplied with sucking discs. The 400 living and 5,000 fossil species are all marine. This class is mentioned in the chart because it has reached a high degree of specialization, entirely beyond other members of the phylum and almost comparable with the specialization of the vertebrates.

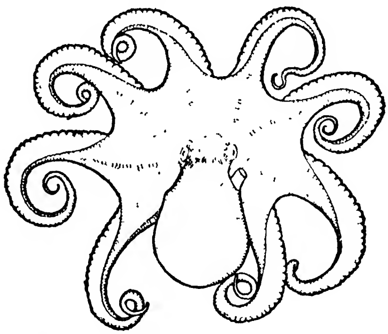


FIG. 57.—Octopus, a cephalopod mollusc, commonly known as a "devil-fish." (After Cowdry.)

Cephalopods may be remembered on account of the immense size attained by some. Squids have been captured which have barrel-shaped bodies 18 feet long with arms reaching out 32 feet more. Such giant squids are known to engage in titanic

submarine struggles with whales, for whales have been captured with their skin marked by long rows of pits where the sucking discs of the squids have left their scars. These squids are reported to be the chief food of the cachalot whale.

Another line of development, branching off near the annelids, gave rise to the huge modern phylum ARTHROPODA (*jointed footed:* crabs, crayfish, spiders, insects, etc.). Animals that are externally segmented and have segmented appendages belong in this group. This is the most highly developed phylum of its line, and its important classes will be described.

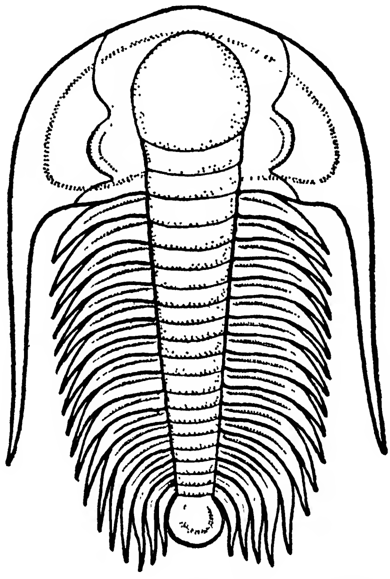


FIG. 58.—A trilobite from the Cambrian. (After Walcott.)

Class TRILOBITA (*three-lobed:* trilobites). Trilobites are extinct arthropods known only in fossil form. The fossils show a head shield, usually semicircular in shape, followed by a varying number of segments divided lengthwise into the three lobes that give the animal its name.

The trilobites are mentioned here, although they have been extinct since the late Paleozoic, because there are larval forms today that resemble these old trilobites. The trilobite larva of the horseshoe crab is an example. The trilobites are only one of the many groups of animals that have become extinct in the course of evolution (see Fig. 74).

Class CRUSTACEA (*crustlike shell:* crayfish, lobsters, crabs, etc.). These are the arthropods with two pairs of antennae. With few exceptions they breathe by means of gills. The group contains some 16,000 species, marine, freshwater, and a few land forms.

The Crustacea are the "insects" of the water. Shoals of minute crustaceans may be so abundant as to discolor the ocean for miles. Swimming through such shoals, the mighty Greenland whales obtain their food by straining myriads of these small organisms through the whalebone fringes of their jaws. These tiny crusta-

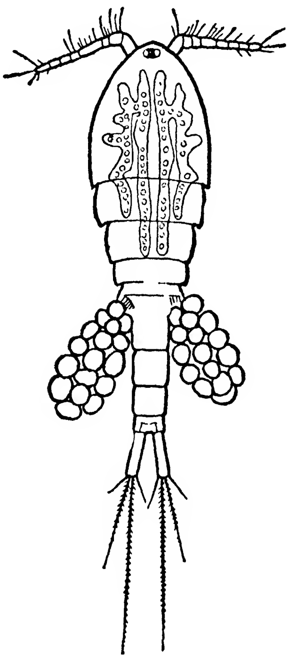


FIG. 59.—A copepod, one of the minute crustaceans abundant both in the ocean and in fresh water. They may be so abundant as to discolor the ocean for miles. ×50 (After Leuckart and Nitsche.)

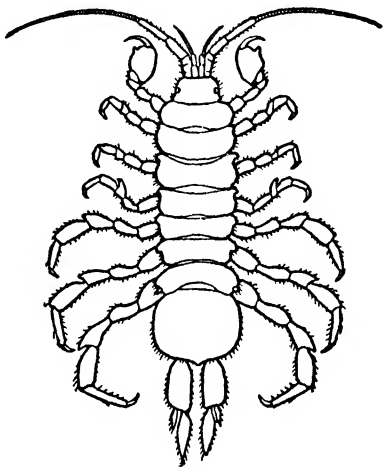


FIG. 60.—A fresh-water isopod. The jointed appendages with a hard outer covering mark this as an arthropod. The two pairs of antennae show that it belongs to the class Crustacea. ×2 (After Richardson.)

ceans affect man more directly in that they are the main source of food of most fish fry and form a considerable part of the diet even of some large fishes. But not all crustaceans are small. Lobsters grow to be 2 feet long, and on the quiet bottom of the deeper ocean are crabs that measure 11 feet from tip to tip of their giant pincers.

Class ONYCHOPHORA (*claw-bearers:* Peripatus). Primitive wormlike arthropods, with tracheae for breathing and one pair of antennae, belong in this class. There are about 75 species, all terrestrial. The importance of this group in demonstrating the relation of insects and annelid worms will be discussed shortly.

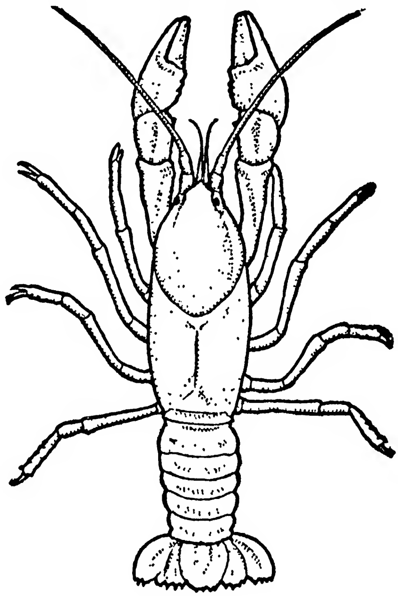


FIG. 61.—A crayfish, representing one of the more specialized groups of crustaceans. (After Ortman.)

Class ARACHNIDA (*from Arachne, the spinner:* spiders, scorpions, etc.). Arachnids are without antennae, with a head-thorax bearing six pairs of appendages and with an abdomen which usually does not carry appendages. Most of the 20,000 species are terrestrial. Spiders are predaceous animals and are beneficial to man in that they help him control his insect enemies, but the ticks and mites that also belong here not only irritate man's flesh and suck his blood but also carry such diseases as Rocky Mountain spotted fever for man and Texas fever for cattle.

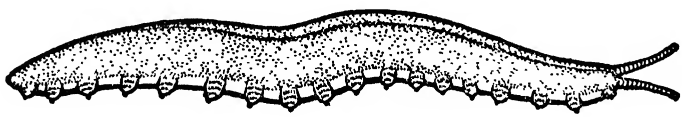


FIG. 62.—*Peripatus,* a connecting link between the insects and the annelid worms. (After Sedgwick.)

The penetrating ability of ticks may be appreciated when one realizes that they can pierce between the plates of a turtle's shell and suck the blood below.

Class MYRIAPODA (*many footed:* centipedes and millipeds). The myriapods are arthropods with one pair of antennae. They breathe by means of tracheae and have a distinctly segmented trunk bearing many similar legs. All the 1,000 species are land-dwelling.

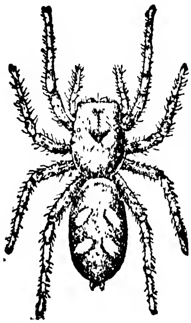


FIG. 63.—A spider. (After Emerton.)

Class INSECTA (*cut into segments:* flies, bees, butterflies, beetles, etc.). These arthropods also have one pair of antennae. They breathe by piping the air directly to the tissues through air tubes called tracheae, the most efficient mode of breathing for small animals yet evolved. The efficiency of this excellent breathing system may be appreciated by observing the tremendous activity of which insects are capable.

Insects have three pairs of legs and are usually winged. The 450,000 or more species are practically limited to the fresh water and land. The importance of insects to man will be indicated near the end of this chapter.

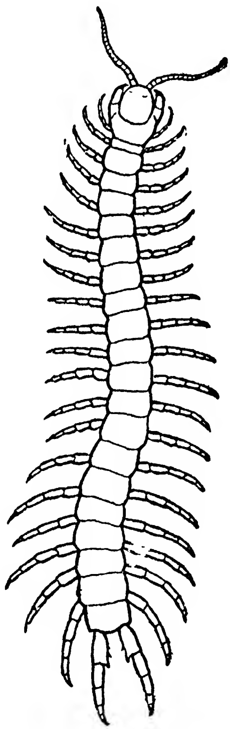


FIG. 64.—A centipede. (After Newport.)

The chordate series.—Starting again with the Coelenterata, the least-developed phylum in the chordate series is that of the NEMATHELMINTHES (*round worms:* nematodes, hookworms, vinegar eels, etc.). These are unsegmented round worms with either a true[1] or a false body cavity and a digestive tract which has both mouth and anus. About 1,500 species have been described, but Cobb, a specialist in the group, estimates that more than 80,000 species are parasitic in the verte-

[1] A true body cavity has a lining of epithelial tissue which the false body cavity lacks.

brates alone, and that the free-living far outnumber the parasitic round worms. In a striking passage he says:

Not the least interesting thing about nematodes is the astounding variety of their habitats. They occur in arid deserts, at the bottoms of lakes and rivers, in the waters of hot springs and in polar seas where the temperature is constantly below the freezing point of fresh water. They were thawed out

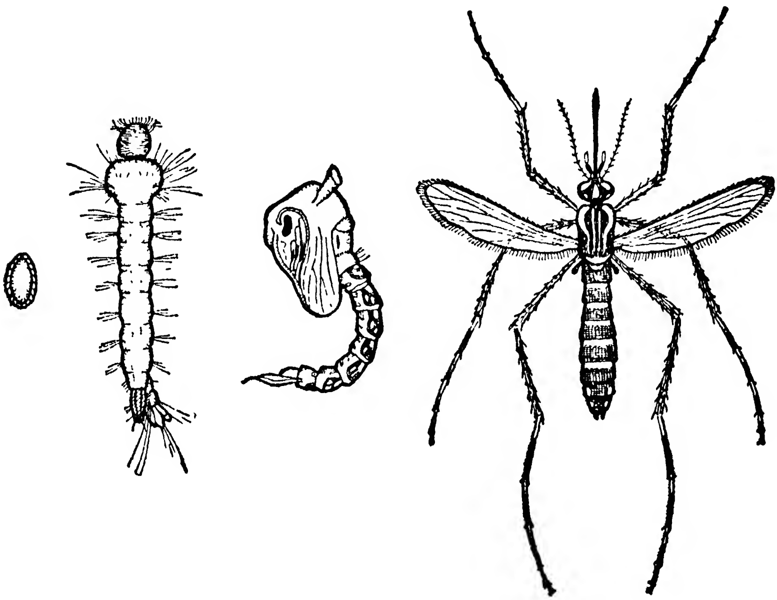


Fig. 65.—The egg, larva, pupa, and adult of the yellow fever mosquito (*Aedes*) which belongs to one of the more specialized of the insect orders. (After Herms, from Howard.)

alive from Antarctic ice in the far South by members of the Shackleton expedition. . . . . In short, if all other matter in the universe, except the nematodes, were swept away, our world would still be dimly recognizable, and if, as disembodied spirits we could then investigate it, we would find its mountains, hills, vales, rivers, lakes, and oceans represented by a film of nematodes. The location of towns would be decipherable, since for every massing of human beings there would be a corresponding massing of certain nematodes. Trees would stand out in ghostly rows representing our streets and highways.

SAGITTA represents one of the aberrant groups of marine worms. They are small, transparent, fin-bearing wormlike animals that appear to belong to this series.

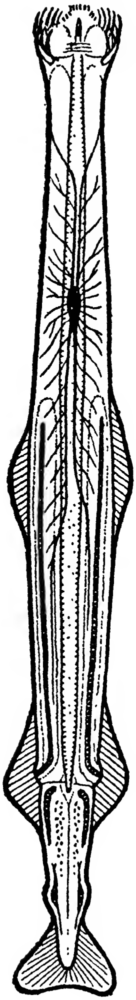


FIG. 67.—Sagitta, an aberrant worm of the Chordate series. (After Lang.)

Phylum ECHINODERMA (*spiny skin:* starfishes, sea urchins, sea cucumbers). Echinoderma are usually radially symmetrical animals with a well-developed coelom. They have a set of tubes carrying water, (a water-vascular system), which operate the tube feet that are frequently used in locomotion. The group takes its name from the fact

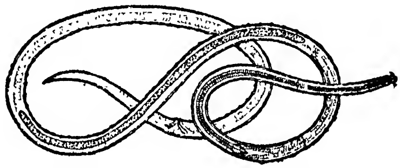


FIG. 66.—A free-living nematode worm, Phylum Nemathelminthes. (After Cobb.)

that the skin is usually armed with spines. There are about 4,000 living species in five classes, all marine.

This is another ancient phylum. Two whole classes have become extinct. The modern representatives show great powers of regenerating lost parts as do the flatworms of the other series. A starfish may grow new tube feet, new arms, or even a new stomach, if its old one gets pinched off in its hazardous method of feeding. This method involves holding open the hinged valves of a clam or oyster, everting the stomach and performing the preliminary digestion within the shell of the victim. In stale water a sea cucumber frequently dispenses with its own digestive apparatus by casting it out of its body and starving while it grows a new one. In the meantime the water may improve and the trick may save its life.

The eggs of some animals can be made to develop in the laboratory without fertilization by spermatozoa. The echinoderm eggs are most easily made to develop by artificial means. Heating, shaking, changing the density of the sea water, or treating with various chemicals will cause these eggs to produce free-swimming blastulae or in some cases more advanced larvae.

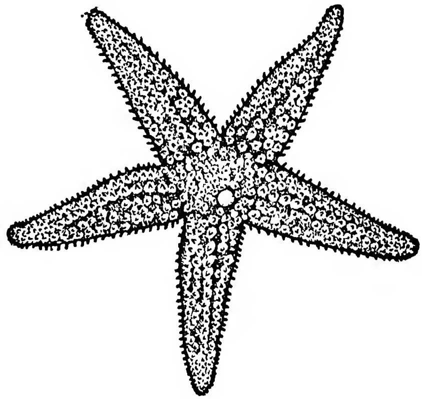


FIG. 68.—*Asterias*, a starfish. (After Coe.)

The phylum BRACHIOPODA may belong in this series rather than in the other. This question is discussed later.

Phylum CHORDATA (*pertaining to the notochord;* Ascidians, Amphioxus, and the vertebrates). Typically these are segmented animals with a dorsal hollow nervous system enlarged at its anterior end to form a brain; with a flexible, rod-like structure called a notochord, the forerunner of the backbone; and with gill slits in either the embryo or the adult. About 37,000 species are described.

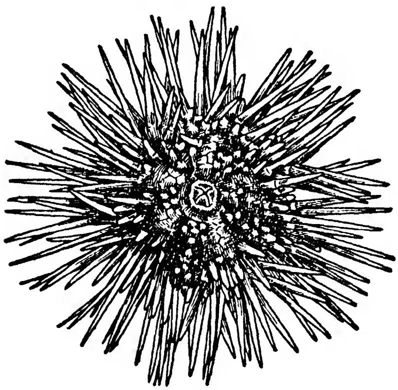


FIG. 69.—*Arbacia*, a sea urchin. (After Coe.)

This is the phylum to which man belongs. There are four subphyla.

Subphylum HEMICHORDATA (*half chordates;* Balanoglossus, or acorn-tongue worm). These are also called ENTEROPNEUSTA, which means that the breathing apparatus (gill slits) is in connection with the alimentary

canal. They are wormlike chordates that burrow in the mud at the bottom of shallow bays. They have a partially developed notochord, a dorsal and a ventral nervous system, and gill slits. All the 25 known species are marine.

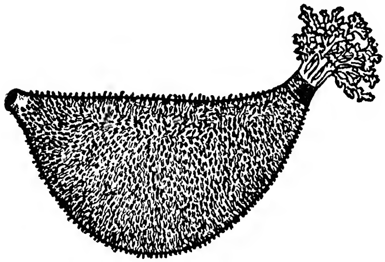


FIG. 70.—*Thyone*, a sea cucumber. The tentacles about the mouth and the small projections over the body are modified tube-feet. (After Coe.)

Subphylum UROCHORDATA (*notochord in tail;* tunicates, ascidians, or sea squirts). These are degenerate saclike marine chordates with a tadpole-like larva in which the notochord is limited to the tail region. Just above the notochord lies the dorsal hollow nervous system. It has an enlarged anterior end which corresponds to the vertebrate brain. The larva swims about for a few hours and then usually settles head-first against the sea bottom or a convenient rock and undergoes a series of markedly degenerative changes. It loses its tail and with it the nerve cord. The brain degenerates to a group of nerve cells such as is usual in lower invertebrates. The skin secretes a tunic largely composed of the stuff known as cellulose, so abundant in plants, and water siphons develop as in bivalved molluscs. In fact, this degenerate adult was thought to be a mollusc until its mode of development from the tadpole larva was discovered.

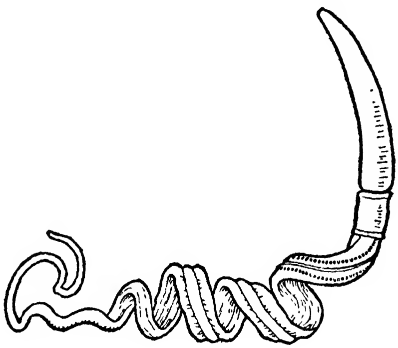


FIG. 71.—*Dolichoglossus*, a hemichordate. (From Newman, after Bateson.)

Subphylum CEPHALOCHORDATA (*notochord even in head;* Amphioxus). These are elongated fish-shaped chordates in which

the notochord and nerve cord extend the full length of the body. The twelve recorded species are all marine.

Subphylum VERTEBRATA (*having vertebrae*). The vertebrates are chordates with a vertebral column and a brain box. Both may be made of cartilage or of bone. There are about 36,000 species, marine, fresh water, and terrestrial.

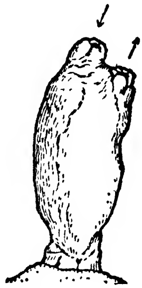


FIG. 72.—An external view of a typical urochordate (a sea-squirt.) The arrows show the direction of the water currents that bring the animal food and oxygen. (After Wilder.)

This subphylum does not come within the scope of the present chapter, but its classes are added for the sake of completeness in surveying the animal kingdom. It includes CYCLOSTOMATA, the lampreys; PISCES, the fish; AMPHIBIA, salamanders, frogs, and toads; REPTILIA, lizards, snakes, and turtles; AVES, birds; and MAMMALIA, the hairy vertebrates.

The evidence.—The relationships indicated in the chart are based on three main lines of evidence: (1) from paleontology, the study of the fossil remains of extinct species and the fossil pedigrees of living forms; (2) from the study of comparative anatomy of adult structures; (3) from the study of the embryonic development of animals, or embryology.

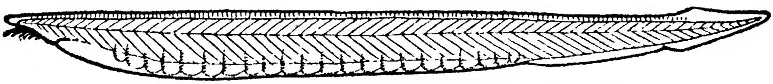


FIG. 73.—*Amphioxus*, a cephalochordate. (From Wilder.)

The conclusions reached from these studies have been tested against evidence furnished by examining the geographic distribution of animals; by subjecting animals to changed environment; by studying the origin and heredity of traits in stocks whose ancestry is known with much precision; and by using delicate chemical tests which reveal chemical similarities in the blood of related forms.

On account of lack of space, presentation of detailed evidence

will be limited to a discussion of some of the data from the first three sources, but none of the omitted evidence conflicts with that presented.

The distinctive evidence furnished by the study of embryology comes from comparisons of developmental stages with the adult and embryonic structures of less highly specialized animals. Such comparisons frequently give clues to relationships otherwise impossible to discover at present. In general, we have reason to believe that the development of the individual is a brief, imperfect summary of the development of its race. This generalization is known as the law of recapitulation[1], and in popular language states that every monkey climbs his own ancestral tree. By applying this law we are able to do two things. We can gain some knowledge of the general appearance of ancestral groups which are otherwise entirely lost. The best example of this type of reconstruction of a lost ancestor will be given later in discussing the ancestry of the echinoderms. Further, we can gain evidence of unsuspected relationships among living animals since the embryos of specialized forms may resemble the adults (or older embryos) of more primitive forms. Such knowledge also helps in the reconstruction of lost ancestral types.

The study of embryology also furnishes material for a comparison of embryonic structures of different embryos. Comparative embryology and comparative anatomy together constitute the science of morphology, which means simply a study of form and structure. The pertinent contribution of the great field of morphology to our quest for relationships is the principle of homology, which holds that structures having similar form and composition and with the same embryonic origin are related. Of the factors involved in determining homology, that of similarity of origin is most important.

With this general statement of the sources of information we may now summarize some of the less technical points of available evidence.

[1] See also discussion of this point in chapter xv by Dr. Bartelmez.

a) *The study of fossils.*—From the study of fossil remains we find that invertebrates inhabited the earth many millions of years ago, since all but possibly the very oldest known rocks contain evidence of living things. (See table I, p. 84). During all this time the fossil records show that most animals living on the earth have been undergoing change, and that each geological era has had its characteristic grouping of animals developed from the life of preceding periods.

The earliest geological records show plants and animals comparatively simple and relatively unspecialized when compared with their modern representatives. With passing time many fossils show an increasing complexity. As conditions changed the numbers of species of different types of animals fluctuated, now decreasing and again increasing. Whole classes became extinct while others were able to live on through many geological eras, as has the genus LINGULA of the Brachiopoda. No species once extinct has been known to reappear. Many of the less specialized forms, FORAMINIFERA of the Protozoa, for example, have persisted little changed for long periods of time side by side with animals that were undergoing decided progress in specialization. Thus not all animals became more specialized, but the general rule holds that the animal forms preserved in the older rocks are less highly specialized than their relatives living today.

We find the first well-preserved fossils at the beginning of the Cambrian period of the Paleozoic era at a time when life had probably already existed on the earth as long as it has since. Before that time we have few traces of definite forms of animal life. The presence of recognized worm trails and of traces of highly developed crustacea in pre-Cambrian rocks indicates the presence of many elaborate invertebrates before the time from which we have good fossil records.

At the beginning of the Cambrian we suddenly find most of the great groups of modern animals represented, usually by relatively simple members. The absence of vertebrates and insects is marked and noteworthy. Such profusion of types existed that

it is generally concluded that more than half of the total evolution of invertebrates had taken place before the beginning of the Cambrian.

Among the animals found in the Cambrian rocks are: Shelled protozoans (Foraminifera), already mentioned, whose lime skeletons allow them to be long preserved. These are much like those still living in our oceans. True sponges were fairly abundant. Coelenterata were represented by jellyfishes, by ancient corals, and by an extinct group called GRAPTOLITES, which first appeared in the Cambrian period and became abundant locally. Worms, being soft bodied, do not easily fossilize, but tracks and borings of marine worms are common in these rocks and form one of the most abundant fossil remains of the time. Brachiopods were abundant and characteristic. Mollusca were represented by small, fairly rare bivalved forms and by simple snails. Cephalopods have not been found in the earlier Cambrian, but they appeared before the period was over. Trilobites belonging to the phylum Arthropoda were the most abundant of all Cambrian fossils. There were a few relatively simple crustaceans and a few arachnids. The Echinoderms were represented by the simplest class, now extinct, and by a few sea cucumbers.

The progress of life of some of the more characteristic animals of the Paleozoic Era is shown in the accompanying diagram from Cleland (p. 289).

At the beginning of the Mesozoic Era trilobites had disappeared and modern corals replaced the more primitive type of the Paleozoic seas. Brachiopods were greatly reduced in numbers and during this era, they, with the Bryozoans, came to occupy their present relatively inconspicuous position in the animal kingdom. The most important invertebrates of the lower Mesozoic were the molluscs, with all the modern classes well developed. During this period the Cephalopoda became strikingly more modern. In the arthropod phylum, lobster and crablike forms appeared among the Crustacea, and first beetles and then bees, wasps, and ants ap-

peared among the insects. The beetles became abundant. By the end of the Mesozoic, sponges and coelenterates had put on their modern form, and the present type of crabs was numerous.

By Tertiary times invertebrates were in most respects very

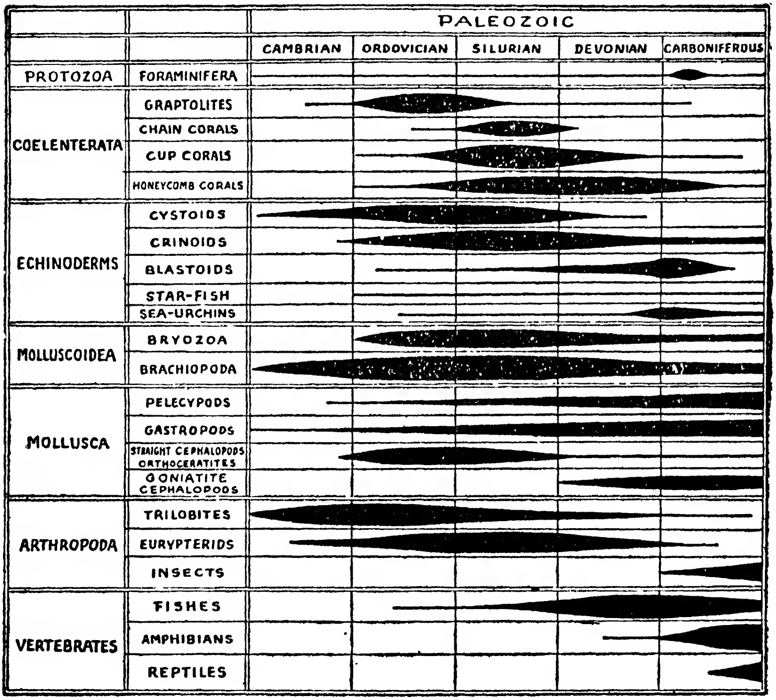


FIG. 74.—Table showing the distribution and relative abundance of life in the Paleozoic. (After **Cleland.**)

much like those we find today. During this period the crabs increased markedly in the water and the insects on the land.

b) *Early embryology.*—Animals start in life as a single cell. Many Protozoa have evolved without adding more cells. In them the course of evolution has been toward the development of specialized cell organs rather than the adding of more cells. In some relatives of Paramecium, for example, a very complex organism

has thus evolved with highly specialized digestive, excretory, and nerve-muscle apparatus. Others, as AMOEBA, have remained relatively simple in structure and more closely resemble the single-celled stages from which higher animals develop. It is interesting in this connection to note that the eggs of some sponges and coelenterates are capable of slow locomotion by the same means used by AMOEBA.

In the majority of the Protozoa, when the adult animal reproduces by cell division, the daughter cells move apart and maintain a separate existence, but in some these new cells remain attached and thus form a colony (Fig. 44). This latter usually happens also when the fertilized egg of a higher animal divides. In early development such a group of cells frequently resembles a mulberry and is called MORULA (the scientific name of the mulberry) on that account. Superficially at least, the morula resembles the simpler of the colonial protozoa.

With further cleavage the developing embryo forms a hollow ball of cells, called a blastula, which is remarkably like the plant-like protozoan called VOLVOX (Fig. 41). The Protozoa have scarcely passed this point in their development. The sponges have passed it but have undergone a particular type of specialization which none of the other animal groups have followed; hence they are shown as occupying the end of a line of development near the bottom of the animal tree.

The Coelenterata and all the higher animals undergo a further embryonic development in which the round, hollow, ball-like, blastula becomes infolded at one pole and at length forms a two-layered structure with the layers tending to touch each other. Such a condition in the developing embryo is called a gastrula and roughly corresponds to the stage of development on which all coelenterate structures are based.

In the gastrula stage the embryo has two sheets of embryonic tissue known as "germ layers." Of these the outer is called the ectoderm and the inner the endoderm. These germ layers occur in all higher animals. In the coelenterates they are separated by

a jelly-like substance which may be reduced to a thin layer or may make up the greater bulk of the adult animal.

All animals except the Protozoa and the sponges pass through these stages, but beyond the Coelenterata differences begin to appear which furnish the reason for dividing the animal kingdom into the arthropod and the chordate series shown in the chart. The first of these differences is concerned with the cleavage of the egg. In the aberrant branch of the animal kingdom which we call the sponges and in the coelenterates the cleavage of the fertilized egg is indeterminate. This means that the divided cells do not contain separate organ-forming substances, but that each cell can reproduce the entire embryo if it should be artificially separated. Beyond the Coelenterata this indeterminate type of cleavage is carried on by the animals of the chordate series, Nemathelminthes perhaps excepted.[1]

The animals of the arthropod series have developed a determinate cleavage, which means that early in the development of the egg the different cleavages do separate specific organ-forming substances, such that if the cells of the new embryo are accidentally separated, each cell cannot reproduce the entire embryo but only the limited part which it could produce if the other cells were also present. This type yields fewer and larger cells at a given stage than does indeterminate cleavage.

Beyond the Coelenterata all animals have three germ layers. The third layer, called the mesoderm, is formed between the other two, but the method of formation is different in each series. In the arthropod series the mesoderm is formed from pole cells located at the junction of the ectoderm and endoderm, near the opening to the primitive gut. In the chordate series it arises primitively from the endoderm of the gut either through the wandering off of individual cells into the space between the endoderm and ectoderm or on the walls of small hollow vesicles budded off to form the coelom, or body cavity.

This difference is diagrammatically shown in Figures 75 (at 4)

[1] Urochordata appear to have independently acquired determinate cleavage.

and 76. The pole cells are located near the opening of the primitive gut; by rapid division they push off two long strings of cells, the mesoderm bands, between the ectoderm and endoderm.

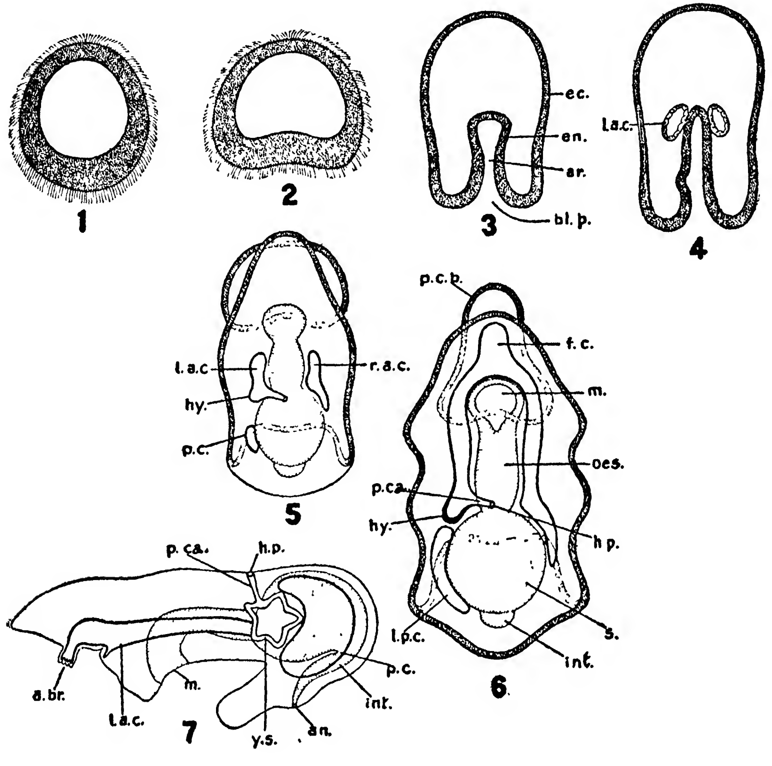


FIG. 75.—Stages in the development of an echinoderm. (1) blastula; (2) early gastrula; (3) late gastrula; (4) early larva with paired coelomic pouches (*l.a.c.*). These pouches arise from the endoderm (*en*) and their walls are made of mesoderm. (*ec*) ectoderm; (*ar*) primitive gut; (*pl.p.*) opening of primitive gut. (From Newman.)

The coelom, when present, also arises differently in the two series. In the annelids it is formed by the hollowing out of the mesoderm bands, while in the echinoderms and lower chordates it arises as an outpocketing from the primitive gut to form the hollow vesicles spoken of above.

In summary, the two series are separated as follows:

Chordate Series	Arthropod Series
Typically, with indeterminate cleavage	Determinate cleavage
Mesoderm from endoderm	Mesoderm from pole cells
Coelom from endoderm pouches	Coelom from hollowing out of mesoderm bands

c) *Larvae that recapitulate.*—The group of phyla included in the bracket marked TROCHOZOA on the chart, including the Platyhelminthes, Nemertinia, Bryozoa, Annelida, Mollusca, and perhaps the Brachiopoda, are all similar in that many of their marine forms have larvae that roughly resemble the adults of some fresh-water rotifers.

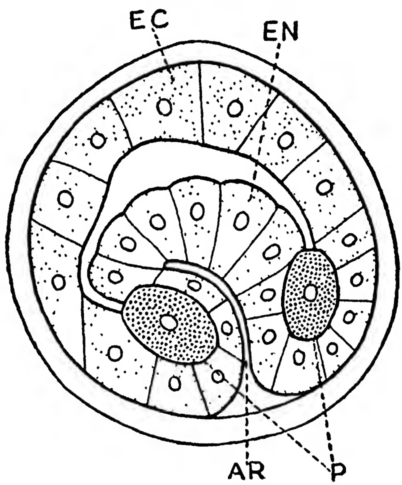


FIG. 76.—The gastrula stage of an annelid worm showing the pole cells which give rise to the mesoderm. *EC*, ectoderm; *P*, pole cells; *EN*, endoderm; *AR*, primitive gut. (Modified from **Hatschek.**)

A typical trochophore larva is pear-shaped with distinct bilateral symmetry. At the broad end, where the blossom occurs in a pear, is a tuft of apical cilia overlying the nerve center of the larva. Farther down, but still nearer the blunt than the small end, are two rows of cilia encircling the body. Since the mouth lies just below, these are called the preoral cilia. Below the mouth, encircling the narrowing part of the pear-shaped body, is another circlet of cilia. The mouth leads into a narrow esophagus which opens into a large stomach, and this in turn opens to the exterior through a short intestine. The anus lies near the stem end of the pear. At the point where the pear stem would appear a tuft of cilia is sometimes found, opposite the apical tuft. A pair of ciliated excretory tubes may also be present.

This general description and the figure given serve fairly well also for the adult rotifer known as TROCHOSPHAERA (Fig. 51, *A*) but it is not certain that they are as closely related as this would

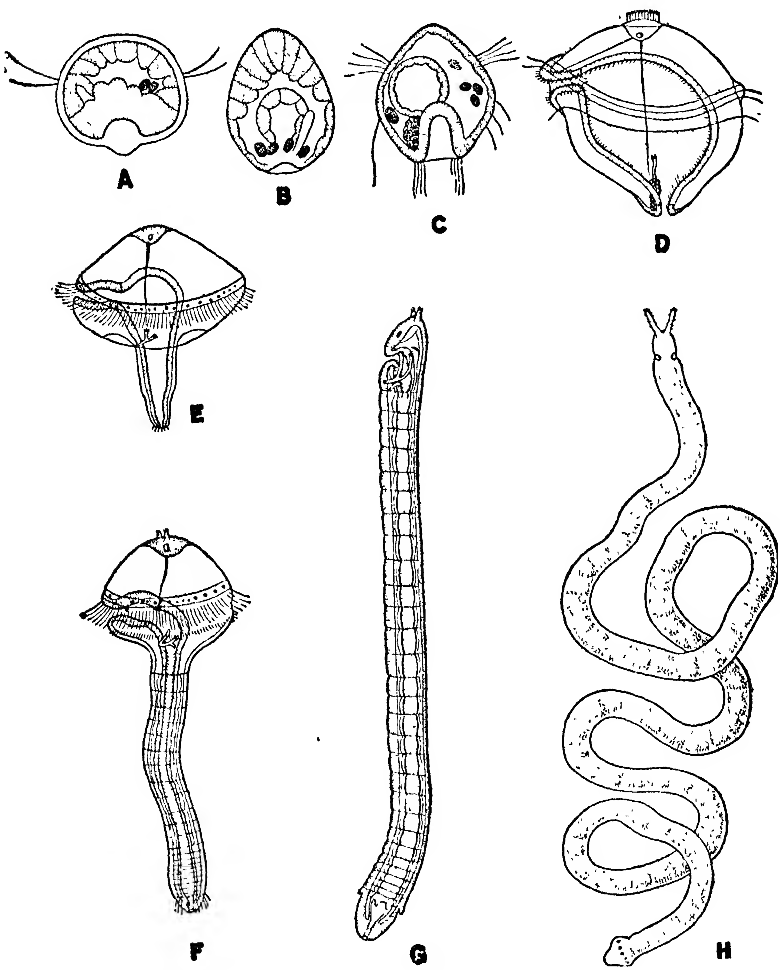


FIG. 77.—Stages in the development of *Polygordius*, a marine annelid. *A*, ciliated blastula; *B*, gastrula; *C*, early trochophore larva; *D*, optical section of trochophore larva; *E*, *F*, *G*, *H*, the transformation of the trochophore into the adult. (From Newman, after Whitman.)

indicate, since the early development of the rotifers is different from that of the typical trochophore larvae.

The larvae of marine flatworms and nemerteans lack the anus and both have lobelike outgrowths which are lacking in the typical trochophore. These are ciliated and seem to indicate a relation with the comblike ciliated plates of the Ctenophora. This resemblance serves to connect this series of larvae with the free-swimming pre-Ctenophora which may have been the ancestors of the Platyhelminthes.

Of all the groups mentioned, the trochophores of the marine annelid worms and of the marine molluscs are most alike and most typical. If the trochophore larva does nothing more than suggest a close relationship between the great phylum of the segmented worms and the still greater one of the snails and bivalved shellfish, it is making a marked contribution to our ideas of the evolution of the invertebrates.

But it does much more than this. MacBride reviews the literature and the facts at length and decides that the trochophore is the modern representative of a free-swimming Ctenophore-like animal which furnished the ancestral form for the great group of phyla we call the Trochozoa. From this great free-swimming group, animals settled in the mud and sand at the bottom of the ocean and became wormlike or mollusc-like, but retained in their free-swimming larvae a resemblance to their Ctenophore ancestors.

Now the Ctenophora greatly resemble the jellyfish of the Phylum Coelenterata, so much so that many modern authors still follow the old custom of placing them as a class in the coelenterate phylum. By this similarity of the trochophores to the old ctenophores and by their similarity to the coelenterates we anchor this series to the stem group. Here we are applying the principle of the law of recapitulation, and we conclude that these phyla, through their larvae, are again passing through a stage of their earlier racial history.

In all fairness it must be stated that there is an alternate

theory to explain the trochophore larvae. It is well known that animals of diverse origin living among similar surroundings tend to become at least superficially alike. Thus burrowing animals tend to assume the general form of a worm regardless of whether they may belong to the worm group, the molluscs, the echinoderms, or the chordates. It is this tendency toward convergence that makes the problem of real relationships so complicated. Zoölogists learned long ago that surface characters are not to be trusted as a means of finding true affinities; that the exterior of an animal may tell merely where it has lived, and that one must explore the internal anatomy and its development to find true relationships.

From the point of view furnished by the principle of convergence, the trochophore larvae represent simply the diverse larvae of unrelated organisms which have become similar because of their living as free-swimming animals in the sea, which does, in fact, present a strikingly constant environment such as might well bring about convergence in different animals exposed to it, but would hardly induce the identical type of cleavage actually found.

We shall reserve final judgment, however, concerning which point of view is more acceptable until we examine the larvae of the Echinoderma and of the Hemichordata of the chordate series.

Larvae of the chordate series.—In the chordate series the echinoderms and the hemichordates also have free-swimming ciliated larvae, but these are built on a somewhat different plan from those of the trochophore group. By indeterminate cleavage a blastula develops which transforms into a gastrula differing from those of the arthropod series by having a large amount of space between the endoderm and the ectoderm. Into this space small hollow vesicles bud off which become the coelom, or body cavity, and whose walls become mesoderm. The different classes of echinoderms have differing larvae but in general they are built on the plan shown in Figure 78.

Typically these larvae are bilaterally symmetrical with an alimentary canal opening through a mouth on the ventral side and

through an anus at the posterior end; to this extent they resemble the trochophore larvae. With the echinoderms, however, the anterior part is enlarged to form a lobe in front of the mouth. Ex-

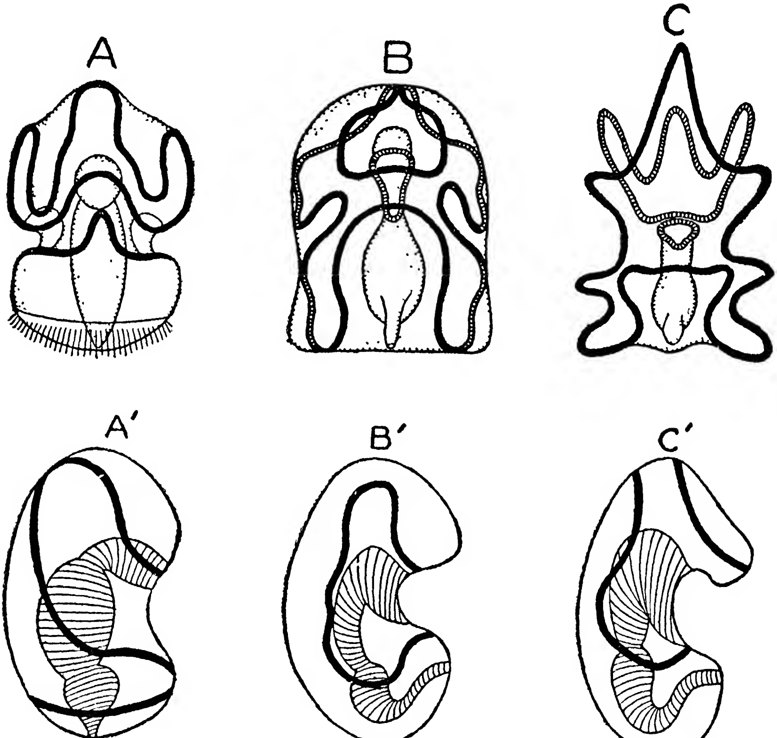


FIG. 78.—A comparison of three larvae from the chordate series shown from two aspects. (*A*) A hemichordate larva; (*B*) the larva of the sea cucumber; (*C*) the larva of the starfish. The first is from the Phylum Chordata, the others from the Echinoderma. (After Wilder.)

ternally there is a band of cilia running in some pattern about the concave ventral surface, but the form of this ciliated band is markedly different from that of the trochophores. Internally there develop three pairs of coelomic pouches which later, in the echinoderms, develop into the coelom and water-vascular system

of the adult. These larvae also lack the definite excretory organs typically found in the trochophores.

The fact that these larvae of the chordate series are essentially similar, although they belong to various classes decidedly differing from one another in the adult stage, has led to the theory that the larvae represent a primitive type of animal which does not exist today and of which no fossil remains have been found, but which has been reconstructed from a synthesis of the characteristics now common to the echinoderm larvae. This hypothetical echinoderm ancestor has been called a Dipleurula. Such an animal would feed by means of ciliated arms containing extensions of the middle pair of coelomic pouches, and in this would resemble the brachiopods of today with their ciliated feeding arms.

As great as is the difference between the Dipleurula type of larva and the trochophore, they have sufficient resemblances to suggest that they may have had a common ancestor. We may allow ourselves to imagine an ocean of primitive times thick with dipleurulas and trochophores, which, if we could only collect and examine, we should probably have assigned to the same class of animals. It is probable that the most important differences between these two types could be traced to the fact that the dipleurulas sprang from a line having indeterminate cleavage, while the trochophores came from one having determinate cleavage.

The existence of these two types of larvae in the ocean at present, where they are exposed to identical conditions, is strong evidence against either having been entirely the product of convergence and favors the view that both have real ancestral significance.

According to this reasoning the chordates are related to the echinoderms, since the larva of the hemichordates bears so striking a resemblance to that of certain echinoderms that when first found it was thought to be a new type of echinoderm larvae. MacBride concludes that there is no important difference between the hemichordate larva and the typical echinoderm larva, but that there is a great difference in the changes that take place before either becomes adult.

It follows that the Echinoderma and the Hemichordata are derived from a common stock of free-swimming marine forms. The main trunk of this common stock continued to be free-swimming and gave rise to the other invertebrate chordates and to the vertebrates, all of whom have free-swimming representatives in the ocean today. The fishes among the vertebrates still dominate the ocean as free-swimming animals; the echinoderms took to the bottom of the ocean and became bottom feeders as they are at present; the sea cucumbers among the echinoderms, and the hemichordates among the early chordate stock became burrowing animals.

Acceptance of this view stands or falls with the relationship of the hemichordata to the true chordates. The most important evidence for the connection is based on homologies of the nerve cord, notochord, and gill slits of these animals with the same structures in the larvae or adults of other classes of the phylum.

Alternate theories of the origin of the vertebrates are reviewed by Wilder in his book, *The History of the Human Body*, and by Newman in *Vertebrate Zoölogy*.

Two uncertain phyla.—It is difficult in the present state of knowledge to place the Nemathelminthes and the Brachiopoda with even the degree of certainty we feel with regard to the preceding phyla. The Nemathelminthes seem to be related to Sagitta, which in turn appears to have been an offshoot from the primitive Dipleurula stock at a time when the coelomic pouches had not yet been cut off from the primitive digestive tract. When the Nemathelminthes do develop a true coelom they do so by the coelomic pouch method of the chordate series. On the other hand, some of the Nemathelminthes appear to have a determinate type of cleavage in which they resemble members of the annelid series. These animals have many parasitic members which have engaged most of the attention given to their group, and the development of free-living representatives has been little studied as yet.

In the Brachiopoda we find an indeterminate type of cleavage and the coelom arises as an outpocketing from the primitive gut; these characteristics we associate with the chordate series. The

development of a nerve plate crowned with a long tuft of cilia, together with the position of the mouth and the presence of annelid-like segments and appendages seem to relate them to an annelid-like trochophore. Perhaps they belong to neither line, but should be represented as constituting another branch from the ancestral coelenterate stock which separated from the others before the arthropod line had developed determinate cleavage.

Arthropod affinities.—There still remain for consideration the relationships of the huge phylum Arthropoda. These segmented animals with segmented appendages are quite obviously related to the annelid stock which was also distinctly segmented, and which, like the primitive arthropods, still bears a pair of appendages for each body segment. In both groups the nervous system is also similar, consisting typically of a bilobed "brain" placed dorsal to the alimentary tract and connected with the ventrally placed chain of ganglia by nerve cords running around the esophagus. Typically, in both, there is a pair of closely joined ganglia in each body segment united with the other ganglia by a double nerve cord.

This early arthropod stock is divided into a number of fairly distinct groups. The most primitive of these, in many ways, is that of the extinct trilobites, which some investigators regard as ancestral to all other arthropod groups, but which appear more closely allied to the primitive crustaceans than to the other arthropods.

The crustaceans are characterized by possessing a distinct larval form, the nauplius larva, found now as a free-living animal only among the more primitive members of the group; but there is good evidence that it appears also as a stage in the developing egg of the more highly specialized crustaceans. The same ancestral stock that produced the crustaceans may well have given rise also to the now extinct trilobite group, the present arachnids, and to the line which now culminates in the insects.

Peripatus: a connecting link.—Regarding the relationship of the arthropods with the annelids we have further evidence fur-

nished by the living connecting-link animal, Peripatus. These animals are widely and disconnectedly distributed over the warmer parts of the earth; they occur in New Zealand, Australia, South Africa, in different unconnected parts of South America, in Central America, Panama, and the West Indies. Such discontinuous, widespread distribution is characteristic of old groups of animals and presumably means that they formerly occupied also much of the intervening space.

Peripatus (Fig. 62) is undoubtedly an arthropod, possessing such marked arthropod characteristics as (*a*) a pair of appendages modified as jaws, (*b*) an arthropod-like heart, (*c*) a space around the heart frequently called the haemocoel, (*d*) without a body cavity around the digestive tract, (*e*) tracheae, which connect it with the insect section of the arthropod phylum.

On the other hand, Peripatus shows strong annelid affinities in these respects: (*a*) soft skin rather than the hardened covering characteristic of arthropods, (*b*) presence of but a single pair of jaws, (*c*) presence of paired annelid-like excretory organs in most segments, (*d*) hollow appendages, (*e*) annelid-like character of the muscular wall, and disposition of the main system of organs.

The developmental history emphasizes these similarities based on homology of adult structures. The egg and early development are closely annelid-like. This similarity continues until there is a row of segmentally arranged bodies, in each one of which appears a cavity just as the coelom appears in the developing annelid segments. From this point the development is like that of the arthropods. Rudiments of appendages appear, the growing annelid-like coelom degenerates into the arthropod form in which the coelom is practically suppressed, and there is an enlargement of blood space. Tracheae appear as growths from the ectoderm and simple eyes are formed as in the insect larvae.

Both by the homology of adult structures and by the law of recapitulation of the history of the race in the development of the individual, Peripatus is seen to represent a connecting link between the annelids and the insects. Similar living connecting links

could be cited between the lower and higher crustaceans and between the myriapods and the insects. The morphological relationships of adult structures, such as the excretory organs or the reproductive organs, could be traced, but this would lead into a maze of technicalities that would only cause infinite confusion to a reader who has not done careful laboratory work in zoölogy.

Numbers and instinct against size and intelligence.—Accompanying the differences in general embryology and morphology here hastily sketched there has also been a difference in the development of the nervous system of the two series. With the arthropods the ganglion chain is developed to its present culmination; but in the other series has arisen the dorsal, hollow tubular system of the vertebrates with its greatly enlarged anterior end, the brain, allowing for a type of mental activity little known in the arthropod series.

In both lines the less specialized animals react mainly by those reflex actions of the entire organism which are commonly called tropisms. In the arthropod series these tropisms evolve into instinctive behavior, most marvelously exhibited near the apex of the series by the social ants. In the other line, reasoning power is added to tropisms and instinctive behavior, culminating in man and accounting for whatever claim to dominance in the animal kingdom he may at present hold.

By most objective evidence available, size of individuals excepted, the insects of the arthropod series, rather than the mammals of the chordate series, are dominant on the earth today. They are most numerous in species and individuals. They are widespread. They practically control the great tropical regions, the most fertile of the globe; only in rare instances, as in the mosquito eradication of the Canal Zone, has man been able to hold them sufficiently in check to go about his work unharmed. In the less productive temperate regions, man is continually alert to circumvent the insects that carry disease to him and threaten to ruin his crops and destroy his food supply. In time this may become the age of man, the most highly developed mentally of the verte-

brates, but at present he is only beginning to dispute the ascendancy of his rivals, the highly specialized insects crowning the arthropod series.

These facts and theories concerning relationships in the animal kingdom are presented without attempting to consider the equally important but less nearly solved problem as to the method by which the evolutionary changes related here have come about. Such a discussion must be left for another chapter (chap. xiii).

SELECTED REFERENCES

1. R. Hertwig (translation by J. S. Kingsley), *General Zoölogy* (Henry Holt & Co., 1912).

2. E. W. MacBride, *Textbook of Embryology*, Vol. I: *The Invertebrata* (The Macmillan Co., 1914). (See sections on relationships at the end of each chapter.)

3. W. J. Miller, *Introduction to Historical Geology* (Van Nostrand Co., 1922).

4. H. H. Newman, *Outlines of General Zoölogy* (The Macmillan Co., 1924).

5. H. H. Newman, *Vertebrate Zoölogy* (The Macmillan Co. 1920).

6. A. F. Shull, *Animal Biology* (McGraw-Hill Book Co., 1914).

CHAPTER XI

THE EVOLUTION OF THE VERTEBRATES

ALFRED S. ROMER

INTRODUCTION

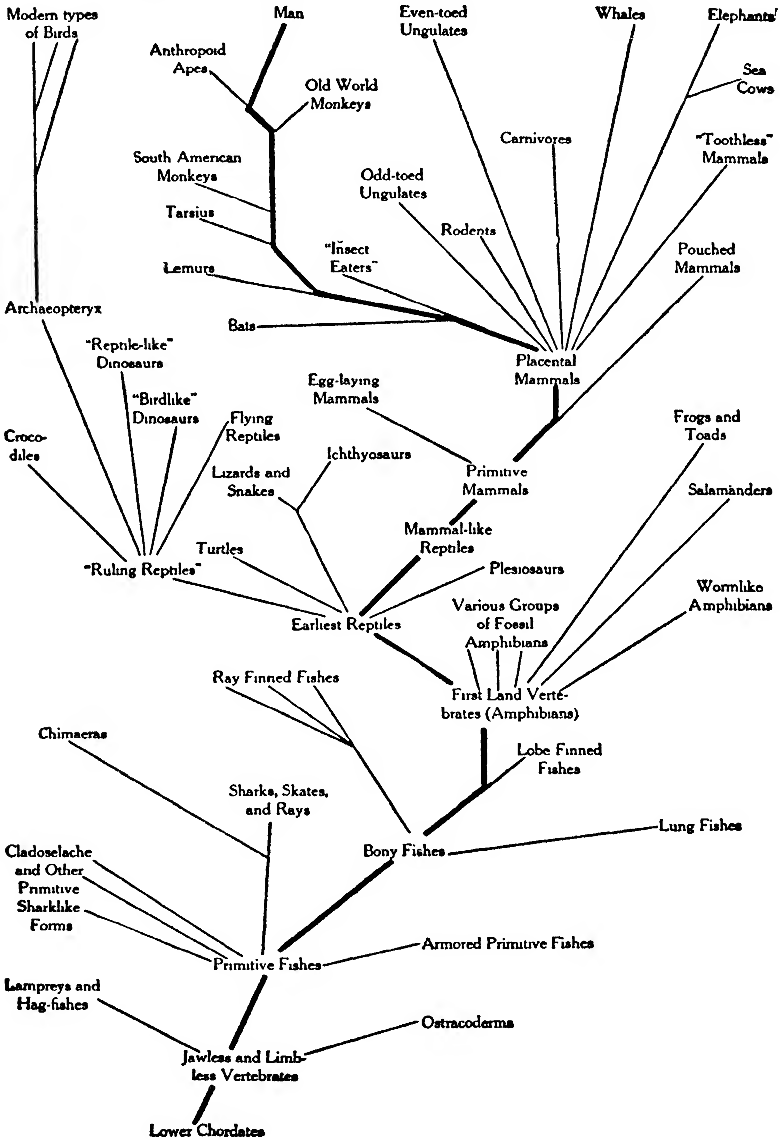
We are to discuss the evolution of the animals that have backbones, the vertebrates. These forms constitute but a relatively small proportion of living things and are a comparatively recent group, without the length of geological history behind them possessed by many other types of plants and animals. They include, however, a great number of the animals familiar to us, such as the fishes, frogs, toads, salamanders, reptiles, birds, and that great group of animals which possess hair or fur and nurse their young, known as the mammals. Further, they are of particular interest because man himself is a member of this group of animals, and the history of their rise includes the story of man's own ancestry.

THE FOSSIL RECORD OF VERTEBRATES.—In the discussion of plant evolution, most of the evidence is drawn from comparative studies of living forms, since most plant tissues do not contain mineralized portions, such as bones and shells. It is difficult, therefore, to trace many of the stages of their development through geological history. In the treatment of animals other than vertebrates, the evolutionary story is also mainly based on evidence obtained from living creatures, since the greater part of the evolution of these forms seems to have taken place before the fossil record becomes at all clear.

In the case of most vertebrates, however, these disadvantages are absent to a great extent. As with other forms, much is to be learned from the study of living types. But in the backboned animals we have a better chance of securing fossil remains of the actual ancestral forms themselves, since, except for some of the lowest and perhaps the earliest types, vertebrates have all pos-

CHART II

A FAMILY TREE OF THE VERTEBRATES, MUCH SIMPLIFIED



sessed hard skeletal parts. Furthermore, but little of the evolution of the vertebrates had been accomplished before our fossil record becomes fairly clear and readable.

Our story of the evolution of vertebrate life is not, of course, complete. A century and a quarter ago the story bound up in the rocks was almost unsuspected. Fifty years ago we were able to grasp at some of the bare outlines of the plot. Today the story of some groups is known in considerable detail; in other lines great gaps still exist. But the work of the student of fossils has barely begun. Perhaps 90 per cent of our knowledge of extinct vertebrates has been gained from but two areas of the earth's surface, Western Europe and North America. Of what went on over most of the world during the greater part of geological time we know almost nothing. Whenever new fields are explored (as exemplified by recent American work in Mongolia) new facts are abundantly brought to light; and even in comparatively well-worked areas our knowledge constantly increases. It is highly improbable that we shall ever fill every gap; too much of the sedimentary record has been worn away or buried. But many pages missing from our history twenty-five or even ten years ago are known today, and we confidently hope that in the not-too-distant future we shall have a coherent knowledge of the descent of all the major groups of vertebrates.

The origin and structure of vertebrates.—For the origin and very earliest stages of the vertebrates little or no fossil record is available; here, at least, we must fall back upon evidences from comparative anatomy and embryology.

At one time or another almost every important group of invertebrates has been suggested as the ancestral type from which the vertebrates have sprung. But, as we have seen, the vertebrates are apparently derived from some member of the lower chordates (best typified today by *Amphioxus*) and the characters of vertebrates are such that they must be considered as belonging to the *Phylum Chordata*. The supporting structure, the notochord, of these lower forms, is found in the embryo of every verte-

brate and in the adults of more primitive forms. The hollow nerve cord running along the back of the typical lower chordate is the spinal cord, the main trunk of the vertebrate nervous system. All the early, water-breathing vertebrates have gill slits, as do the lower chordates. Air-breathing types lose them as adults, but gill pouches, at least, invariably occur somewhere in the early stages of every vertebrate, even man.

The vertebrates, however, have added new features. In even the more primitive living and fossil forms, there is found at the anterior end of the spinal cord a well-developed brain, the main pattern of which can be followed throughout the rest of the series. Sense organs, too, were developed, a nostril or nostrils, eyes and ears (the last primitively related to the sense of balance, rather than hearing).

In this respect, it is true, the vertebrates merely paralleled other animal types such as the insects in which similar organs were developing. Brain development later became a very important factor in the evolution of the group. But the most characteristic feature of the early vertebrates was their unique type of skeleton, an internal skeleton, buried within the body of the animal, in marked contrast to the external skeleton of many invertebrates.

Around the notochord was formed a series of connected structures forming the vertebral column, or backbone, from which the name of the group is derived. Other internal supporting structures developed, such as a brain case around the developing brain, and bars between the gill slits that stiffened them.

The skeletal parts were, it seems, formed at first of cartilage (gristle), a comparatively weak material. Later in history this was replaced and added to by that much stronger substance, bone; and in the early development of every human being today the story of the appearance first of cartilage and then of bone is repeated.

Primitive jawless and limbless vertebrates. (Fig. 79).—From what has been said, we have reason to believe that the more

primitive vertebrates possessed an internal skeleton composed of cartilage only. Consequently we can hardly hope to find their remains as fossils, for under ordinary circumstances cartilage (unlike bone) is not preserved in the rocks. We obtain evidence of the primitive forms only from lowly vertebrates that have survived from the early days to the present, or from the earliest which acquired hard skeletal parts. From these two sources we catch glimpses of early vertebrate history.

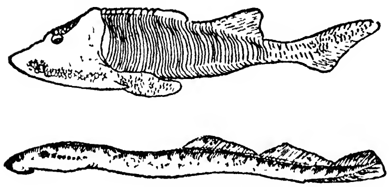


FIG. 79.—Jawless and limbless vertebrates. Above, a fossil ostracoderm, *Cephalaspis* (after Goodrich); below, a living lamprey. (After Dean.)

Living today in various parts of the world are certain lowly vertebrates known as the lampreys and hag fishes, eel-shaped, water-living animals, which prey upon fish into whose flesh they eat by means of a tonguelike rasping organ. Since their skeleton consists of cartilage they have left no fossil record. Although quite specialized in many ways, they are on a lower plane of development than any fish in such respects as the absence of jaws and the absence of paired fins or limbs. These animals suggest to us that jaws and limbs were not present in the earliest vertebrates, but were a later acquisition. The lampreys and hag fishes, however, are too specialized in their mode of life to be themselves considered as survivors of the actual ancestral vertebrates.

Quite different at first sight are the earliest vertebrates found in the fossil record (the oldest skeletons are Silurian, although possible vertebrate remains are found as far back as the Cambrian). These early types are called the *Ostracoderms*, "shell-skinned." Like the lampreys and hag fishes, they were quite primitive in that they had no jaws and no limbs. They were remarkable, however, for the fact that most of them had a protective covering of bone or other hard substance (to which the name refers) in addition to their internal skeleton.

Our knowledge of these two primitive but contrasting groups leads us to believe that there once existed close relatives of the ostracoderms, very much like the more generalized members of this group, but lacking armor and hence not preserved as fossils. Some of these, by gaining hard shells, were thus brought into our field of knowledge as fossils; others gave rise to the surviving lampreys and hag fishes; and still others gave rise to true fishes and through them to all later vertebrates.

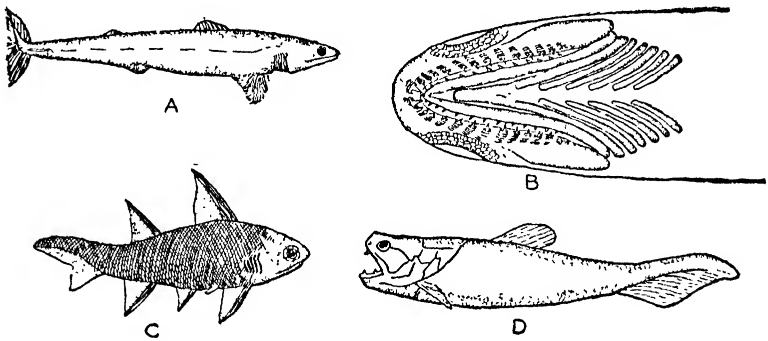


FIG. 80.—Sharklike fishes. *A*, a primitive fossil form, *Cladoselache*. *B*, the under side of the head of *Cladoselache*, showing the resemblance of the jaws, armed with teeth, to the gill arches behind them. *C*, a fossil spiny shark, *Diplacanthus*, with the rudiments of an extra pair of limbs represented by spines lying between the fins representing the arms and legs. *D*, an aberrant armored fossil relative of the sharks, *Dinichthys*. (*A* and *B* after Dean, *C* after Traquair, *D* after Hussakof.)

PRIMITIVE FISHES; DEVELOPMENT OF JAWS AND LIMBS. (Fig. 80.)—The Devonian period is commonly known as the "Age of Fishes," for in it we see, in a comparatively short time, the development of almost every important group of fishes of which we have knowledge. Among them are a number of primitive shark-like forms, one of which, *Cladoselache*, comes very close to our idea of what a primitive fish should be. Here we are quite surely dealing with a well-developed vertebrate, for the rocks have preserved for us many characteristic skeletal features. But it was more than a vertebrate; it was a true fish.

Cladoselache possessed limbs in the shape of paired fins,

stiffened with bars of cartilage, at the sides of the body, corresponding to the arms and legs of higher forms. These fins are broad at the base, and while we have no stage below this, it is probable that they arose as flaplike outgrowths of the edges of the body, just as the unpaired fins on the back and tail of fish have arisen. In addition to fins, biting jaws with teeth are present. Between the gill slits of water-living vertebrates are small supporting skeletal bars, usually divided into upper and lower portions. The jaws, when they develop, lie just in front of the gills, and like the other bars are divided into upper and lower halves. It is believed that jaws, as we first see them, are merely a front pair of these gill supports, modified to serve another purpose. (Both development and nerve supply strongly support this idea.) At first (and in many fishes today) the jaws are not attached firmly to the skull but consist of upper and lower bars only loosely attached to the rest of the skeleton. The primitive teeth with which the jaws are armed are quite similar to the little denticles which cover the skin of sharks.

In these primitive fishes, then, we have something new in the world. Besides the advantages of an internal skeleton, common to all vertebrates, they have paired fins of great use to them in swimming and balancing, and tooth-bearing jaws which can be adapted to a much wider range of food materials.

With these advances accomplished, the evolution of the fishes with a skeleton of cartilage advanced rapidly, geologically speaking; even in the Devonian we find many types of these. One group (peculiar in having spines placed in front of the fins) shows a remarkable feature. All other vertebrates have at the most but two pairs of fins, corresponding to arms and legs. Some of these little forms, however, have one or more additional pairs of spines between the principal ones. It seems, then, that the primitive fishes had not "settled down" to a definite number of limbs; at first there was some variation.

Most of these primitive sharklike forms disappeared early from the scene. In the next period, however, we find remains of

forms more nearly related to the living sharks, and today the sharks, the skates, and the rays (which are flattened-out, bottom-living sharks), and the quaint chimaeras of the deep seas remain as the living remnants of these primitive fishes.

BONY FISHES; SKELETAL DEVELOPMENT; LUNGS. (Fig. 81.)—Almost as early as any of the sharklike types, and apparently derived from them, appeared the second of the two great groups into which the fishes are divided—the bony fishes, representing a

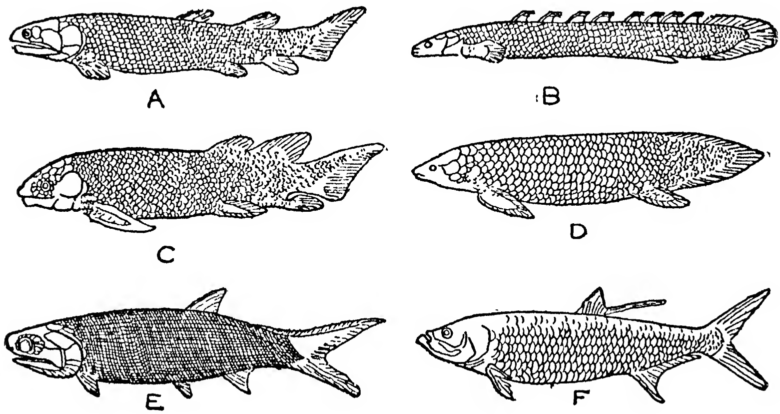


FIG. 81.—Bony fishes. *A*, an ancient fossil lobe-finned fish, *Osteolepis*. *B*, a modern representative, *Polypterus*. *C*, an ancient lung-fish, *Dipterus*. *D*, the living Australian lung-fish, *Ceratodus*. *E*, a fossil ray-finned fish, *Palaeoniscus*. *F*, an example of the living ray-finned fishes, the tarpon. (*A*, *C*, and *E* after Traquair, *B* after Bridge, *D* after Gunther, *F* after Goode.)

further step in vertebrate evolution. These include the vast majority of living fishes and the ancestors of the land forms as well. They have proved successful. Let us inquire into the reasons for their success.

They are *bony* fishes. This was not the first appearance of bone in the world, for some ostracoderms and some sharklike forms had bone: bone may be a very old thing in the life of vertebrates. But it is only in this group that it seems to have been used to its greatest advantage. Bone is a protection against enemies. Many of these fishes were of small size, but over the top and

sides and bottom of their heads, over their gills and shoulder regions, there developed a series of bony plates, usually in a definite pattern, traces of which are still to be found in our own skull (see Fig. 99), while down over the rest of their bodies extended a series of scales, at first of bonelike structure.

Bone is also found within, lining the mouth and replacing to a great extent the cartilages of the skull, of the backbone, and of the limb skeleton and thereby strengthening these structures.

Another great advance was the development of an apparatus used in breathing air. Whether the primitive vertebrates originally inhabited fresh or salt water is uncertain; these bony fishes, however, were certainly fresh-water forms, and, we believe, inhabitants of bodies of water subject to seasonal drought. The development of lungs enabled them to gain a better supply of oxygen than that available in the stagnant pools in which they were at times forced to live. (We may note, however, that in most modern fishes, which live under different conditions, this breathing organ has been greatly modified.)

Several distinct groups arose from the primitive bony fish type. Probably the most primitive is that of the "lobe-finned" fishes, which are also believed to be the ancestors of all land types. Of these lobe-finned forms, only two survive at the present day in the rivers of tropical Africa, where conditions presumably are somewhat similar to those under which their Devonian ancestors lived. Related to them are the "lung-fishes" proper, abundant in the Palaeozoic, and represented today by three forms (*Ceratodus*, etc.) inhabiting the southern continents. In these the lungs are well developed, and some are able, by burrowing, to withstand the complete drying up of the surface water.

A third bony fish group is that of the "ray-finned" fishes. In other groups a lobe of flesh projects into the fins; in this group, the fins are supported merely by horny rays. These forms were at first unimportant; but by the Mesozoic they had increased enormously in numbers, and spread from streams and lakes into the sea. Today they constitute a vast majority of living fishes.

Every fish with which the ordinary reader would be familiar (except for the sharks) is a member of this group.

The first land dwellers; the amphibians. (Fig. 82.)—So far we have followed the history of vertebrates in the water. We are now to follow them in what is perhaps the greatest single step in vertebrate evolution, their emergence onto land. We have already seen the development of most of the requisites for this step—limbs in the form of paired fins with fleshy lobes; a strong bony skeleton capable of supporting the body when out of the water; and lungs for air breathing. Given the possibility of an air-breathing animal able to support its body on sturdy fins, it might have been predicted that a land form would arise at an early geological period; and this was indeed the case. Near the close of the Devonian the print of a foot appears in the rocks, and in sediments of the following period we find skeletons of the first amphibians, the earliest vertebrates to walk on land.

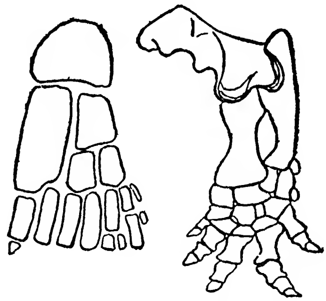


Fig. 82.—A comparison of the skeleton of the "arm" of a fossil amphibian, *Eryops* (at right), with the corresponding fin of a lobe-finned fish, *Sauripterus*, showing the general similarity in the arrangement of the bony elements. (After Gregory, Miner, and Noble.)

The common amphibians ("double livers") of today are the frogs and toads and salamanders. Many are at home on land and in the water, as the name indicates. The eggs of amphibians are usually laid in the water; the young live there, breathing by means of gills. Later on, the gills are usually lost, lungs and limbs are developed, and the animal leaves the water for the land. But while this developmental history appears to have held true throughout, the amphibians of the old days were little like the modern remnants of the group.

The ancient amphibians were still very fishlike and resembled in many ways the lobe-finned fishes from which we believe them

to have arisen. The main difference lay in the limbs. Instead of the comparatively weak paired fins of the fishes, we find these structures developed into legs. They are still rather weak and short, and the animal must have crawled along very slowly and with considerable difficulty. But he could walk, however poorly, a thing almost unknown among fishes. The first great step onto the land had thus been made.

Even this feature, however, had been foreshadowed in the lobe-finned fishes (Fig. 81). Their fins are sturdier than those of most other fishes, and the skeleton inside them is very suggestive of that found in the primitive land forms, sometimes with one bone in the first joint, two in the second, and a branching arrangement beyond, just as man has one bone from the shoulder to the elbow, two from the elbow to the wrist, and then a breaking up of the system into the bones of the wrist and fingers.

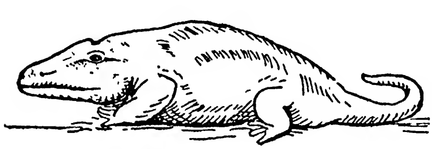


Fig. 83.—*Eryops*, a palaeozic amphibian. (After Williston.)

Why did the amphibians come onto the land? We find the earliest forms apparently spending the greater part of their lives in the water, living much the same lives as their lobe-finned fish cousins. They did not come ashore to escape enemies, for they were as large as any forms in the streams in which they lived; not to breathe air, for that can be done at the surface of the water; not to seek food, for they were carnivorous fish eaters and there would be little for them to eat on land. The answer is an unexpected one. The early amphibians probably came ashore, paradoxical as it may seem, in order to get back into the water.

As we have said, the land waters of those days were probably liable to seasonal drought. This difficulty in the primitive bony fish had been partially overcome by the development of lungs; if the pool were to become stagnant they could still survive. If the pool dried up completely, most of the fish must die, although some

might survive for a short time at least by burrowing into the mud. But the amphibian could crawl overland, although perhaps quite slowly at first, and reach the nearest pool still filled with water. His walking on land was probably due, then, to the necessity of getting back into the water.

Later, of course, some might begin to linger along the banks of dry and drying pools and enter them only to obtain food. Some might find land food available. Others might prey upon their smaller relatives. And so, gradually, a land fauna might be built up.

In the long run, however, the amphibian has not been a success. Except under conditions where streams commonly dry up, he is at a disadvantage in the water as compared with his fishy relatives. In the next period (unfortunately for himself) he gave rise to the reptiles, which were much better fitted for terrestrial life. And so, long ago, crowded out of the water and off the land, most of the amphibian groups became extinct, leaving only a few odd types, the frogs and toads and salamanders, and a few small wormlike tropical forms as living representatives of this once important class.

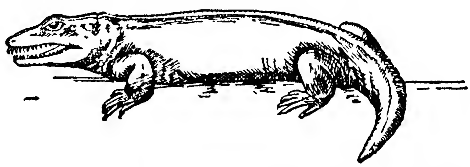


Fig. 84.—The most primitive known reptile, *Seymouria*. (After Williston.)

Primitive reptiles; emancipation from the water.—The amphibians are land forms only in a limited sense, for they are chained to the water whence they came. If land dwellers, they must usually return to the pools and streams at each breeding season to lay their eggs, and there their young, as "tadpoles," must live for a time, swimmers and water breathers. The water has a powerful hold on them; they seldom live far from it, and the whole life of many forms is spent in that element.

While the great coal swamps of the Pennsylvanian period still existed, a new type of land animal, the reptile, appears to have arisen, and to have left the water definitely behind it. (Fig. 84.)

The reptile differs from the amphibian in its mode of development. The eggs of a reptile are laid on land. A tough shell and egg membranes protect the developing embryos from harm and the danger of drying. Yellow yolk inside supplies nourishment for them until they are ready to hatch and emerge as full-fledged land dwellers and air breathers. The handicap of having to adjust themselves first to a water and then to a land existence is removed.

This difference is the only one we know which surely separates all reptiles from all amphibians. We do not, of course, know much of the embryonic development of fossil forms; hence we must distinguish the two groups by their skeletons. As between a modern reptile and a modern amphibian this can easily be done. But in the case of the early types it is practically impossible. We have so completely bridged the evolutionary gap between reptiles and amphibians that it is difficult to draw a dividing line between them. We do not know a single feature of importance that absolutely distinguishes the skeleton of one from that of the other.

As this would imply, the early reptiles were still very primitive creatures, and still quite clumsy in their gait. But with their "release" from the water there appeared, even in the Permian, swifter and more agile types. The long Mesozoic Era which followed is known as the "Age of Reptiles" during which this group dominated the land, the air, and even re-entered and dominated the water with a wealth of amazing forms.

The Ruling Reptiles.—One very important reptilian group is that often known by a term translatable as the "Ruling Reptiles." These were the dominant types throughout the Mesozoic on the land and in the air. In almost all of them there seems to have been a tendency toward a greater degree of activity than is usual in reptiles as we know them today. Many of the early Ruling Reptiles were small, swift-running bipeds, standing semi-erect on their hind legs.

From such beginnings came the dinosaurs. The name is familiar to most readers as that of a group of gigantic extinct reptiles. But this idea is not entirely correct. Many, it is true, were large;

others were much smaller than some living lizards. Further, there were two distinct groups of dinosaurs, not closely related, except that both belonged to the Ruling Reptile stock.

One great group of dinosaurs is characterized by a structure of the hip bones much like that of the crocodile and other reptilian

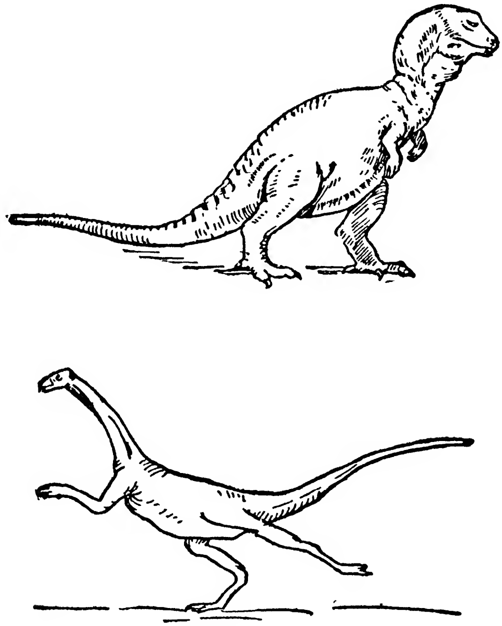


FIG. 85.—Above, a giant carnivorous dinosaur, *Tyrannosaurus*, 21 feet in height. Below, a smaller and swifter relative, *Struthiomimus*. (After Osborn and Knight.)

types, and may be called for convenience the "reptile-like" dinosaurs. These started as small carnivorous bipeds. As we follow them through the Age of Reptiles we find that many of them increased in size, until in the final stages we find giant flesh-eating forms with skulls as much as five feet in length, armed with a battery of saw-edged teeth a foot long; they had powerful hind limbs upon which they ran, but relatively tiny "arms." (Fig. 85.)

Related to the last is another group very different in appear-

ance. (Fig. 86.) These forms early abandoned their carnivorous mode of life, and became eaters of soft vegetation. They abandoned the bipedal mode of progression, and came back to walking on all fours. Many increased enormously in size and became such familiar animals as *Diplodocus* and *Brontosaurus*. These were the largest creatures that ever walked.[1] *Diplodocus*, counting his long slim tail, was well over 80 feet in length. Another member of this group, with long limbs and neck, could easily have looked over the

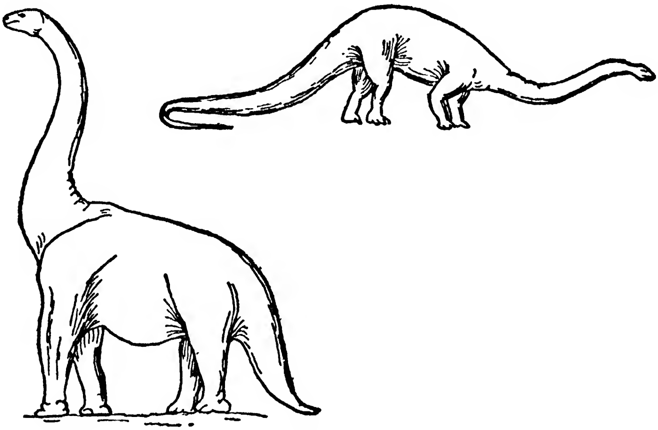


FIG. 86.—Two giant herbivorous "reptile-like" dinosaurs. *Diplodocus*, at the right, measured $84\frac{1}{2}$ feet in length; *Brachiosaurus*, at the left, was shorter but more massive. (*Brachiosaurus* after Abel.)

top of an ordinary four-story building. The weight of one of these animals—by no means the largest—has been carefully computed at $37\frac{1}{2}$ tons, and others in all probability exceed 50 tons.

The second of the two great dinosaur groups (Fig 87) had a rather birdlike structure of the hip region, and we may call them the "birdlike" dinosaurs (although they are not themselves the ancestors of birds). Just as in the reptile-like forms, the more primitive types were light, swift-running bipeds; but unlike that group, there were no carnivores among them; they were all

[1] Not the largest creatures that ever existed, however, for some whales, which do not have to support their bodies outside of the water, are larger.

vegetable feeders. The forms which remained bipedal never grew to the great size of the carnivores, but toward the end of the age of reptiles culminated in the duck-billed dinosaurs and curious

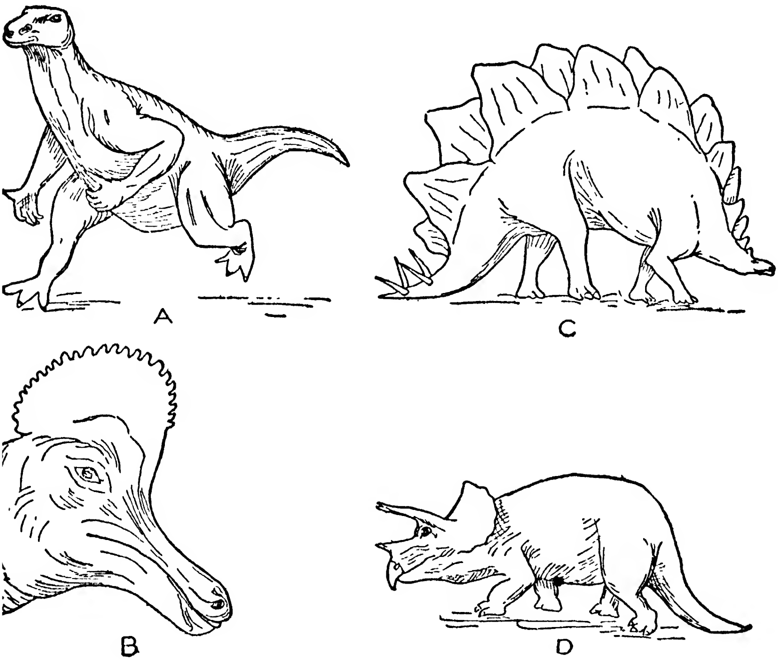


FIG. 87.—Some "bird-like" dinosaurs. *A*, a bipedal type, the European *Iguanodon*. *B*, the head of a crested "duckbill." *Corythosaurus*. *C*, an armored dinosaur, *Stegosaurus*. *D*, a horned dinosaur, *Triceratops*. (*A* after Heilmann, *B* after Gilmore, *C* mainly after Abel, *D* after Knight.)

crested forms which measured on the average about 20 feet in length.

As in the reptile-like dinosaurs, many of the birdlike forms reverted to walking on all fours. None of these secondarily four-footed types seems to have attained a very great size; 20 feet or so from snout to tail was about the maximum. But they present an interesting appearance because of the devices by which they were protected, partially at least, against the huge carnivores of

those days, from which a four-footed beast could not easily escape by running. In one group we find a covering, or armor, in the shape of rows of plates and spines down the back, or bony plates forming a thickly studded shield. Another type, the horned dinosaurs, possessed a long bony shield growing back from the head over the neck, and usually well developed horns on the forehead and nose.

Another group of Ruling Reptiles (and hence related to the dinosaurs) is that of the flying reptiles. (Fig. 88.) In these, a rather batlike method of flying was evolved, by means of a membrane stretched from the arms. But unlike the bats, only one finger (the fourth) became enormously elongated to support the wing. Some of these reptiles became quite large; the wing spread of one type reached 28 feet, far exceeding that of any known bird, past or present.

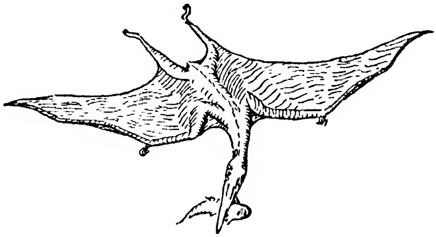


FIG. 88.—A fossil flying reptile, *Pterodactylus*. (After Abel.)

The groups just considered flourished during the great age of reptiles, many millions of years long; but by its end they had all become extinct. Today there survives of the Ruling Reptiles only one comparatively insignificant branch, the alligators and the crocodiles, which are close relatives of the dinosaurs and the flying reptiles. It is an interesting fact that, although an alligator commonly walks on all fours, it can, when pressed, raise itself and run rapidly on its hind legs much as did many of its dinosaurian relatives long ago.

The Ruling Reptiles themselves are nearly extinct. But from them has descended one group which has been a great success—the **birds**. A modern bird differs from an ordinary reptile in many features. It is warm-blooded; it is clothed with feathers; the arms have been transformed into wings; the teeth have been replaced

by a horny bill; the reptilian tail has been largely lost, and is replaced by a tuft of feathers. But even in living birds there are reptilian features. Teeth are present in the bird embryo. Feathers we believe to be merely modified reptilian scales. The feet of birds are so similar to those of dinosaurs that the footprints of the latter found so abundantly in the Triassic rocks of the Connecticut valley were at first thought to be those of gigantic birds. In the Jurassic rocks of Germany, two skeletons of an animal, *Archaeopteryx* (Fig. 89), have been discovered which give us a glimpse of an early stage in the evolution of birds from the Ruling Reptiles. In many respects *Archaeopteryx* is quite reptilian. There is a long, dinosaur-like tail, with feathers arranged along the sides. Teeth are still present in this animal (and in other fossil birds). The "wings" bear feathers, but they are still dinosaur-like "arms," with clawed fingers. This is a bird, but a very reptile-like bird, indeed. Birds, as is often stated, are merely "glorified reptiles," and close relatives of the dinosaurs.

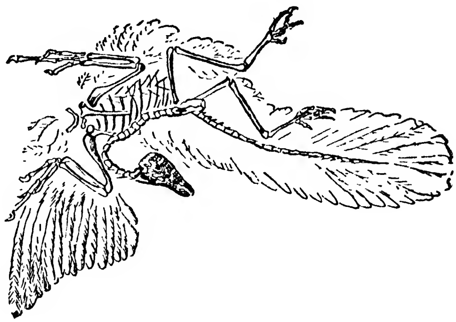


FIG. 89.—One of the two known specimens of the oldest fossil bird, *Archaeopteryx*, as found in the rock, showing the clawed "wings," the long tail and the impressions of the feathers. (After Dames.)

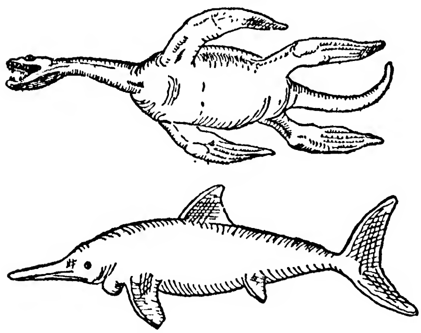


FIG. 90.—Two fossil marine reptiles. Above, *Plesiosaurus*. (After E. Fraas.) Below, an ichthyosaur, *Stenopterygius*. (After Drevermann and Abel.)

WATER REPTILES. (Fig. 90.)—In but few cases did the Ruling

Reptiles attempt to enter the water. Other reptilian groups, however, left the land and entered upon a marine type of life, to become eaters of the ray-finned fishes which abounded in the Mesozoic seas. One group of these is known as the Ichthyosaurs, the "fishlike reptiles," a name which appropriately describes their general appearance. The head terminated in a pointed beak adapted to fish-catching; the body was compressed and high, as in many fast swimming fishes; impressions of the body show us that there was a fin on the back, as in fishes, while the end of the backbone was turned down into the lower end of a sharklike tail. The limbs, once adapted for walking on land, were converted into paddle-like balancers. In all probability these animals, although air breathers, spent their entire lives in the water, and it is possible that they did not come ashore even to lay eggs, but hatched out their young within the mother's body while at sea.

Another type of marine reptiles were the Plesiosaurs, which swam in a very different fashion. They did not move by undulations of the tail and body as do most fishes and "fish-reptiles," for the tail was short and the body flat. Instead, the limbs were elongated into long "oars," by means of which they "rowed" themselves through the water. Very probably they were surface livers, while the "fish-reptiles" were porpoise-like diving types.

Neither of these groups survived the end of the Mesozoic; the end of the Age of Reptiles found them extinct.

We might, if space permitted, continue with descriptions of many other reptilian types. At no time in the history of the earth, perhaps, was there a more interesting and peculiar assemblage of animals than that which lived in the Age of Reptiles. But their day is a thing of the past; only a few survivors of that great host, such as the lizards and snakes and turtles, have come down living to us.

THE ORIGIN OF MAMMALS.—While this great drama of reptilian evolution was being played, another line of evolutionary progress was beginning, quite inconspicuously: the evolution of the mammals, the warm-blooded, hairy, active group of creatures

which nurse their young. Even before the Age of Reptiles had begun, this evolutionary process was under way. In the Permian, we find reptiles which tended to become rather lightly built, and active four-footed running types, showing mammal-like features in their skeletons; and as the Age of Reptiles commences, we find (especially in South Africa) remains of many members of a group known as the mammal-like reptiles (Fig. 91). Few of them were of any great size, many were no larger than a rat or a squirrel. Their limbs were brought underneath the body, as they are in a dog or cat, and not sprawled out sidewise as in a primitive reptile. They were still reptilian in many ways, but with many mammalian features in their skeletons, especially in their skull and jaws. Tooth changes may be taken as an example. Usually in reptiles the teeth are replaced indefinitely. In mammals there are but two sets, the "milk" teeth and the permanent set; and there is evidence that this was the case in the mammal-like reptiles. In most reptiles the teeth in the front and back portions of the mouth are much alike. In mammals, and in these mammal-like reptiles, the teeth are differentiated into "nipping" teeth, or incisors, in front, a canine, or "dog tooth," and a series of grinding "molar" teeth behind. In these respects, as in others, these animals were on the way to becoming mammals.

FIG. 91.—A fossil mammal-like reptile, *Cynognathus*. (After Gregory and Camp.)

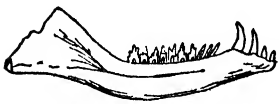


FIG. 92.—The jaw of a mesozoic mammal, *Dromatherium*, twice natural size. (After Osborn.)

After a relatively short period, geologically speaking, these mammal-like reptiles disappeared, but left as their heirs and successors the earliest mammals, found in the Triassic.

The remains of the early mammals which lived during the Age of Reptiles are very scanty, and consist mainly of teeth and of jaws, which seldom exceeded an inch or so in length (Fig. 92).

These little animals were no match in strength for most of the contemporary reptiles. The teeth tell us that they were for the most part eaters of insects, as are still many small mammals today. But as to many features of the primitive mammals, the fossils tell us nothing. Fortunately, however, there are living today in the Australian region two survivors (although much modified) of the primitive mammals—the "duckbill" and the spiny ant-eater. These are mammals, for they are fur-covered and they nurse their young, although in a primitive way. The brain is much more highly developed than that of any reptile. They are "warm-blooded" (that is, with a mechanism for regulating their own body temperature, while that of a reptile varies with the surrounding temperature), but only partially so, as is also true of the human infant. But in one respect they are still quite reptilian: in contrast with all other mammalian types, they still lay eggs.

From these two lines of evidence, then, we are able to catch a glimpse of the primitive mammals of the Mesozoic. Small creatures, insect eaters, swift of limb and alert to escape their reptilian enemies; hair-covered and partially warm-blooded, and hence independent of sunshine and warmth for maximum activity; still egg-layers, but capable of nursing the young when hatched. Such, it would seem, was the condition of mammals for many millions of years while the dinosaurs were supreme.

Two advances here call for special comment. Even the most primitive existing mammals are much superior to any reptile in brain development. The cerebral hemispheres, which in the lower vertebrates usually constitute but a modest part of the bulk of the brain, have increased greatly in size, and with this has come a wider range of intelligent adaptation to the environment. The reptile is, to a much greater extent, an automaton; the mammal has greater ability to learn, to bring the effects of individual experience to bear upon its conduct. The most important organ of memory has begun its chief development.

In most lower vertebrates the young receive no attention from their parents. Consequently, in order to survive, the young reptile

must emerge from its egg as a tiny replica of the adult, ready to take up an independent existence. But in the mammal, with the development of nursing, and in the bird, with the nesting habit, there is no such necessity. The young mammal is nourished and protected by its mother. The period during which it can continue to develop is lengthened. Its structures have more time to grow and attain more nearly adult size before it is compelled to shift for itself. Youth has appeared. And with this comes the first possibility of training the developing mind.

THE MARSUPIALS.—During the Age of Reptiles a further advance was made by the mammals. They began to bear their young alive. The reptilian egg, although protected by membranes and a shell, is still liable to be broken or to be eaten by other animals. The primitive mammals undoubtedly stood by their young until hatched, but at the cost of a temporary restriction of freedom. Toward the end of the Age of Reptiles we begin to find the remains of animals much like the living opossum, which indicate that at that time the pouched mammals, or marsupials, had been evolved. Here the eggs are retained within the body of the mother until they "hatch" (a condition also found in a number of other animal forms). The young when born are still very small and immature (less than an inch in length in opossum) and usually spend the nursing period in a pouch on the belly of the mother where they temporarily grow fast to the nipples.

Most of the living members of this group, except the opossum and a few other forms, are found only in the Australian region, into which these animals apparently migrated near the close of the Age of Reptiles. Before later types of mammals were evolved, this continent was shut off by water from the rest of the world, and these lowly mammals were left there to evolve without competition along their own lines. Besides the kangaroo and other bizarre animals, there are in Australia today parallels to many of the higher mammals of other parts of the world, a "wolf," "cats," a "mole," a "bear," "squirrels," etc. These are similar in appearance and habits to the corresponding animals of other continents

to which these names are properly applied, but (except that they are mammals) are quite unrelated to them.

Placental mammals.—With the development of the young within the mother's body come new possibilities. In the reptile the unhatched young depend for food upon the yolk stored in the egg. In the mammal, however, comes the possibility of the transmission of nourishment from the mother to the unborn offspring. Even in some of the marsupials and, indeed, in a few lower vertebrates, a structure which serves this purpose is present; but the placenta, as this organ is called, is characteristically developed in the group of placental mammals. The blood vessels in the membrane surrounding the developing animal in the body of the mother are brought close to the maternal tissues so that nourishment may pass through; no yolk is necessary in the "egg," though a rudimentary yolk sac is present, and the animal may undergo a far greater amount of development before birth than was previously possible.

At the time that this last advance in mammalian evolution was accomplished, the long Age of Reptiles had come to an end. Most of the great reptilian groups were extinct. The long period of preparation of the tiny early mammals was over and their opportunity for the conquest of the earth had come. The continents lay before them, almost barren of vertebrate life. The earth was theirs, and swiftly at the dawn of the Tertiary, they multiplied and diversified and took possession.

During the Eocene period with which the Tertiary began, a large number of mammalian types were evolved, many of which have long since disappeared: there arose great beasts in which the growth of the body outstripped that of the brain. Early hoofed forms browsed upon the vegetation of those days, a vegetation which was beginning to assume a modern character. Other mammals, the earliest carnivores, became adapted to feed upon them, and we see horned defenses developing in some of the prey. But meanwhile other groups had been advancing, not so fast but more steadily, and most of these archaic types, the eaters and the eaten,

pass out of the story and give place to animals swifter of limb or keener of brain. These latter are the ancestors of the familiar members of the modern mammalian fauna, and we may consider briefly the evolution of some of the best-known groups.

The ungulates.—As we have stated, the dawn of the Age of Mammals found the earth clothed with a palatable vegetation, and many of the newly evolved placentals became capable of feeding upon vegetable matter. Broad-crowned teeth, capable of thoroughly masticating food were developed, and in some mammals which began to feed upon grasses, characteristically gritty in texture, the teeth were further modified. Herbivorous animals, as vegetable feeders are called, are usually harmless folk, and a prey to carnivores. With the necessity for escape from enemies and the possibility of long journeys in search of pasturage, many of these herbivores took to running swiftly on the tips of the toes, upon claws modified into hoofs. Such animals are called ungulates (*ungule*, a hoof), and the two greatest groups of ungulates contain many animals familiar to all of us.

One of these groups is that of the odd-toed ungulates, of which the horse, the rhinoceros, and the tapir are living members. How they attained their mode of locomotion can be understood by a simple experiment. Place the palm of the hand flat on a surface before you. Some animals walk in this manner. Raise the wrist, and presently the hand will rest on the fingers alone, a position in which many animals can run with considerable speed. Then continue to raise, and the hand will rest on the tips of the fingers. Lift still more, and the thumb will not touch, and its usefulness is gone. This leaves a four-fingered (or four-toed) condition, found in the forefoot of the earliest horses which we find as fossils, and in many extinct rhinoceroses. A little farther, and the little finger fails to touch, leaving three digits functioning, a condition found in the living rhinoceroses and many fossil horses. And finally, a slight further elevation, and the hand rests merely on the tip of the middle finger. This is the condition found in the modern horse. All animals run faster on their toes than on the flat of the

foot; as these ungulates took to running more and more on the tips of the toes, the central ones became stronger and the shorter lateral ones were reduced.

The history of the horses is better known than that of most groups of animals. We see them first in the Eocene, as small creatures, about the size of a fox-terrier, already browsers, with limbs somewhat slim and elongated, and having four toes in front (the thumb had already disappeared) and three behind, but with splints (vestiges) of the side toes still present in the hind foot (Fig. 93). As time went on the horses increased in size, the teeth became adapted to grass-eating, the limbs became more slender, and three toes were present in both front and hind feet Gradually the two side toes became smaller and smaller, while the size of the animal continued to increase, until we arrive at the horses and zebras and asses of today, of much larger size and with but one functional toe on each foot.

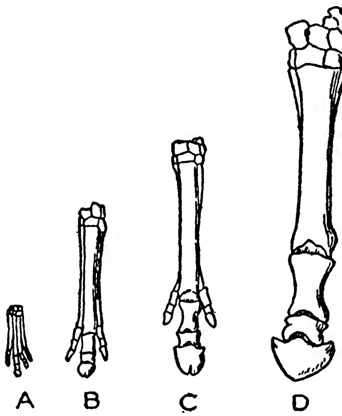


Fig. 93.—The evolution of the forefoot of the horse. *A*, *Eohippus* of the Eocene, with four toes (the "thumb" already gone). *B*, *Mesohippus*, of the Oligocene, with three functional toes. *C*, *Hipparion*, of the Miocene and Pliocene, with the side toes reduced. *D*, the modern one-toed horse, with splints of the side toes. (*A*, modified, after Marsh; *C* after Osborn.)

The rhinoceroses are relatives of the horses which have had a varied history. The living forms are large and powerful horned animals (the horns, incidentally, are not true horns, but a mass of hair firmly matted together). The earliest were of a slender and somewhat horselike build; while, on the other hand, some later fossil types were very short-legged and clumsy and proportioned very much like a hippopotamus. Some fossil types were horned, but a larger proportion were hornless. Some were much smaller

than the rhinoceroses of today; while one extinct Asiatic member of the group was much larger than any elephant (Fig. 94).

The tapirs, now found in the tropics of South America and Asia, are comparatively conservative members of the ungulate group, and give us in some respects an idea of the habits of the early browsing horses. The Titanotheres ("titanic beasts") were archaic members of this group, in which the brain underwent little expansion, while the body grew to very large size; the last members of the Titanotheres had huge defensive horns (Fig. 95), but their slow wits and slow gait appear to have been the reason for their extermination, which occurred early in the Age of Mammals. A final group of relatives of the horses and rhinoceroses was the most peculiar of all, the Chalicotheres, which were quite normal members of the odd-toed ungulates in most respects, but possessed great claws instead of hoofs (Fig. 96). What these were used for is a puzzle (the group is now extinct); perhaps they were used for digging roots.

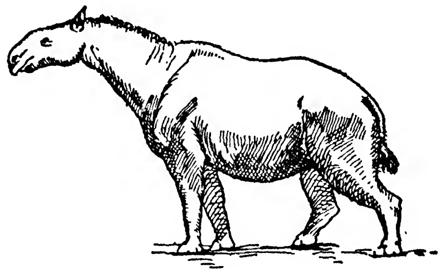


FIG. 94.—A giant fossil hornless rhinoceros from Asia, *Baluchitherium*. (Modified from Osborn and Knight.)

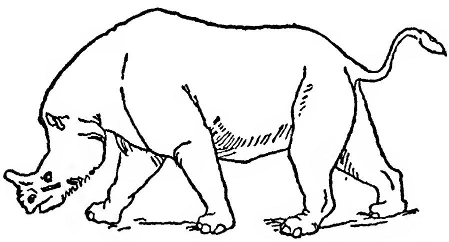


FIG. 95.—The *titanothere*, giant fossil odd-toed ungulate. (After Scott.)

A second great group of ungulates, which is not at all closely related to those just discussed, but parallels them closely in form and function, is that of the even-toed ungulates. To see how the foot of the even-toed types has been attained, let us repeat our

previous experiment to the point where the thumb is lifted free. Then settle the remaining four fingers firmly on the table, and lift. The index finger and little finger will come free, leaving two fingers for support; the "cloven hoof" of the pig or cow or camel is in reality composed of the closely associated third and fourth fingers or toes (Fig. 97).

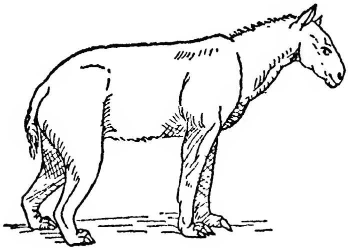


FIG. 96.—The Chalicothere *Moropus*, a clawed relative of the horse. (After Scott.)

In our fossil record we find many remains of these animals. On the whole, while the odd-toed types underwent most of their evolutionary history in North America, the greater part of the even-toed forms seem to have evolved in the old world. The pigs and the hippopotamus (which is a giant water-living "pig") seem to have been old-world products, although a race of giant hogs and the peccaries are found in the American fossil record. All that group of animals which possess horns of true horny material, such as the cattle, bisons, sheep, goats, and antelopes, seem to have been most abundant in the eastern hemisphere; they are but sparsely represented in our own rocks. On the other hand, the camels, although extinct in North America today, underwent much of their evolution here, and have only recently died out on this continent, leaving the existing llamas

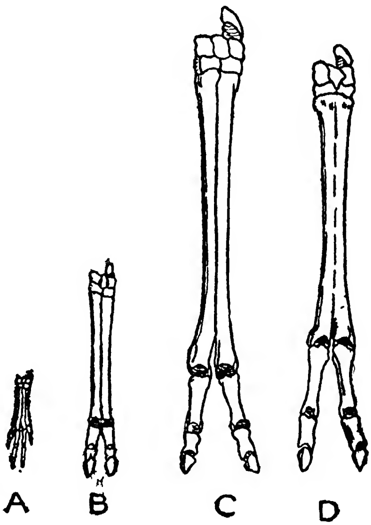


FIG. 97.—The evolution of the front foot of the camels. *A*, an Eocene camel. *B*, an Oligocene form. *C*, Miocene. *D*, the South American Guanaco. (After Scott.)

in South America, and their larger cousins, the true camels, in the old world. The deer family, with antlers of bone shed each year, has left a number of primitive forms inscribed in the fossil records of both North America and Europe.

Carnivores.—Throughout vertebrate history there has never been an abundance of herbivorous forms without carnivores present which fed upon them; and the mammals are no exception to this rule. The earliest mammals were insect eaters, and only lacked size to become potential feeders on flesh. We have mentioned above the archaic carnivores. These soon disappeared, except for one comparatively swift and clever family, from which the various living flesh-eaters have descended. The lions and tigers, and "cats" in general, form one branch of this group which had a successful history; the saber-tooth tigers (Fig. 98), with their great dagger-like canine teeth, were a side branch which persisted down to the Pleistocene. The hyenas and civets of the old world are relatives of the "cats." Another great stem of the carnivores is that which has the dogs and wolves and foxes as its central forms; a host of wolflike forms has appeared in succession throughout most of the Age of Mammals. The raccoon is merely a tree-living dog type; the bears are huge clumsy relatives of the dogs which have in great measure abandoned a carnivorous mode of life. Not quite so closely related to the dogs is that group of small carnivores of which the weasel, the otter, and skunk are well-known members.

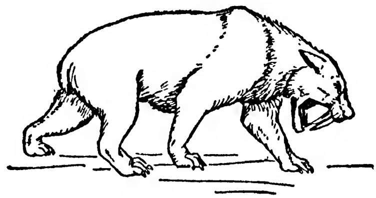


Fig. 98.—The sabre-tooth tiger of the Pleistocene of California. (After Matthew and Knight.)

Another group of flesh-eaters returned to the sea, becoming feeders on fish or molluscs and using their hind limbs as swimming organs in place of the tail. These are the seals and sea lions and walruses, which constitute one of the three mammalian groups that have been able to enter successfully upon a marine existence.

Other mammalian orders.—We have just sketched rapidly the history of three typical mammalian orders. We might continue with outlines of the deployment of many other groups of considerable interest, the evolution of which was already under way in Eocene time and has continued to the present: (1) The elephants, which we can see evolving from small early African types with but the beginnings of tusks and trunk. (2) Their close relatives, the sea cows of tropical seas. (3) The so-called "toothless" forms (edentates), such as the tree sloths and armadillos of South America and their giant relatives which lived in this country not very many thousands of years ago. (4) The gnawing animals, the rodents, including rats and mice and squirrels and the like, which are so numerous today. (5) The whales, which early entered the water and, although descended from land forms, are now so completely aquatic that if stranded on a beach they perish. We might, if space permitted, continue with the history of many other interesting groups of mammals. But let us turn our attention to a matter of more personal interest. During this great radiation of the various mammalian types, where were our own ancestors? What were they doing?

PRIMATES

Primate beginnings; arboreal life.—There are many gaps, as we have said, in our geological history of the evolution of the vertebrates, and this is especially true of our knowledge of our own mammalian relatives, the lemurs, monkeys, apes, and their fossil ancestors. Before much was known of the fossil history, however, the broad outlines of the story were obvious from a consideration of living forms alone, and all our ancient records, as we slowly acquire them, tend to confirm these conclusions. The reasons for our ignorance are not far to seek. Apart from man, the members of this group, known as the primates, are not numerous, comparatively, at the present day, and it is probable that they never have been. Hence our chances of finding specimens of them are small. Further, they have been for the most part forest dwell-

ers, and sediments in which fossils might be preserved are not often laid down in forested regions. Then, too, the primates seem to have been for the most part dwellers in warm climates, whereas most of our paleontological knowledge has been gained from regions in Europe and North America which have had a temperate climate through a great part of the Age of Mammals. Our record is thus an incomplete one; but even so, year by year new evidence crops up piece by piece. Forty years ago, for instance, we knew of but one extinct type of manlike creature; twenty years ago, but two; today we know five. Our story is gradually shaping itself. The main outline of this story, as we shall here present it, is that of the evolution of animals well fitted for a tree-living life and then, in the case of our own ancestors, the reversal of this process and the assumption of life on the ground. We shall see the development, among other things, of four important characteristics—of erect posture, of acute vision, of the hand, of the cerebral hemispheres. It is upon the mental development that our attention is focused at the close of this history. But the evolution of each of these is inextricably bound up with that of the others.

The structure of an animal which has taken up an arboreal life may be greatly modified. Walking on all fours along the branches as the earliest primates did, and jumping from limb to limb, requires considerable agility and co-ordination, and this in itself postulates a greater ability to learn. The arms and legs may be considerably modified in correlation with this type of locomotion. In most true arboreal animals the hold upon the tree is accomplished by digging sharp claws into the bark. In the primates, however, this is usually accomplished by grasping the branch between the four fingers and the thumb or the four smaller toes and the big toe; and flat nails are usually present rather than sharp claws. In the lower primates the grasping power is more especially true of the big toe; a new-born human infant still shows traces of this primitive arboreal character.

A point which was apparently at first of more importance was the development of the sense of sight, in contrast to the sense of

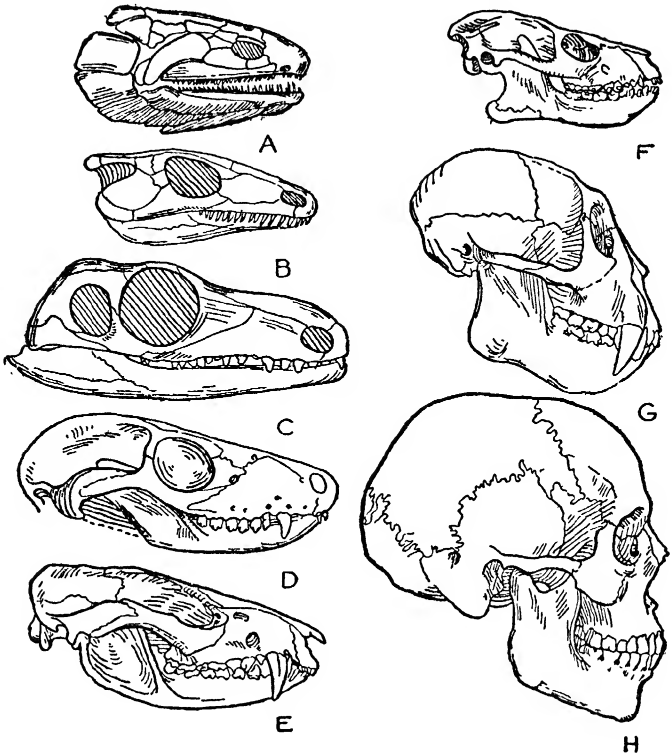


Fig. 99.—The evolution of the skull from fish to man. *A*, a lobe-finned bony fish, *Eusthenopteron*. *B*, a primitive land form, *Seymouria*. The main change is in the loss of the bones at the rear which protected the gills in the fish. *C*, a primitive mammal-like reptile, *Mycterosaurus*. An opening has developed in the side of the skull which accommodates the jaw muscles. *D*, an advanced mammal-like reptile, *Ictidopsis*. The temporal opening has enlarged, leaving a bar beneath it and between it and the eye openings (orbits); the teeth are differentiated into incisors, canines, and molars; and the skull foreshadows that of the mammals in many ways. *E*, a primitive mammal, the opossum. This skull resembles that of the mammal-like reptiles in general appearance; but it is advanced in a number of ways, such as the loss of a number of bones in the skull and jaws, and the breaking down of the bar behind the orbits. *F*, a fossil lemur, *Notharctus*. The brain case is somewhat expanded; a bar has been rebuilt back of the orbits. *G*, the Old World monkey. The brain case is still larger; the eyes are turned forward, with a solid partition between them and the temporal region; the tooth row and "snout" are shortened. *H*, the human skull. The further changes here are mostly concerned with the great growth of the brain case, and the shortening of the tooth row and face. (After Gregory.)

smell. In most animals smell is the most important of the senses, rivaled only by hearing. A dog recognizes his friends or enemies by smell; man and most primates recognize an object or animal mainly by sight. To a tree-living creature the mere presence of an enemy in the neighborhood is of little consequence; the important fact is: *where* is he? In the tree or on the ground? In this tree or one from which he cannot reach me? Can I see him? Smell gives distance; sight gives position as well. Then, too, in rapid locomotion in the tree, sight is of more importance than on the ground. The distance to the next branch must be estimated, its strength calculated. These things are correlated with a decrease of the importance of the sense of smell, an increase in visual observation, and a corresponding increase in intelligence.

FIG. 100.—A living Madagascar lemur. (After Beddard.)

The lemurs are the lowest of the stages in this primate line of development. As fossils they are found in some of the oldest deposits of the Age of Mammals (Eocene) in Europe and in North America. Later they disappear from those regions, and are to be found living today in the tropical parts of the old world, a great number of them being small shy inhabitants of the forests of Madagascar (Fig. 100). Most of them are good arboreal types, but have advanced little from their primitive mammalian ancestors. The eyes are fairly well developed, but there is a doglike muzzle, and the nose is still important. In them, primate evolution had barely begun before it ceased at this low level.

Tarsius; the dominance of sight.—The lemur still depends in great measure upon the nose rather than the eye. This condition is reversed in the next type in the series of primate advances. In the East Indies today is found a tiny tree-living creature, *Tarsius*, whose relatives are abundant in the Eocene rocks (Fig. 101). This little nocturnal beast has two large eyes, directed forward, as they

are in a monkey or a man, and not sidewise as in the lemurs. He can observe an object with both eyes at once. Sight has advanced greatly. In contrast, the long, doglike muzzle of the lemurs has disappeared; the nostrils are reduced in size. We have a face, rather than a snout. Sight has supplanted smell.

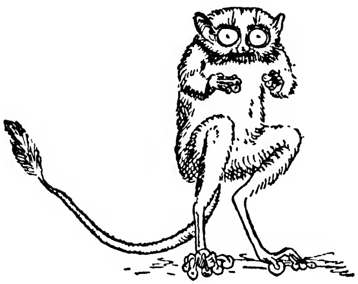


FIG. 101.—*Tarsius*, a living form descended from Eocene types intermediate between the lemurs and higher primates. (After Brehm.)

The monkeys; development of hand and eye.—The advance just described, as our records tell us, had taken place in the Eocene, after which the primates disappear from North America. From then until the time (not very many thousands of years ago) when the ancestors of the Indians entered this country, not one sure trace of a primate has been found in this continent. The next stage in our story, the evolution of monkey-like forms, finds the primates split geographically into two groups. One group of monkeys has migrated to South America, where they are still found today. These, however, are but a side branch of the primate line; the later history of the group is to be traced in the old world, where the oldest monkeys are found in the Oligocene.

In the monkeys the advances made in little *Tarsius* and his relatives are continued. *Tarsius* can look at an object with both eyes, but he cannot focus effectively upon it; he cannot, it is believed, get the effect of depth; he lacks stereoscopic vision. Further, the eyes of *Tarsius* are so constructed that the finer details of objects cannot be made out. These "defects" are not present in the eyes of monkeys. The eye of the monkey is essentially as highly developed as that of man.

The monkey, like all his ancestors, is still a four-footed walker, but he sits erect upon his haunches. The front feet are momentarily freed from locomotor necessities. Even in the lemur these

front feet are flexible structures. In the monkey they are more than feet—they are hands and are used as such. And here we have the beginnings of a character of the utmost importance in human development. Man's appreciation of the world about him is enhanced greatly by his visual observation. But perhaps equally important is his ability to grasp an object in his hand, to examine it, to test it. Further, the effects of man upon the world about him have been produced chiefly by his ability to make and use tools. But without the hand, which is in a sense man's primary tool, this would have been impossible of accomplishment. Suppose ourselves, for the moment, possessed of our proper intelligence, but having the body of a dog or that of a horse. Of what use would be man's superior intelligence if he were unable to make or use the simplest form of tool or mechanism?

With these new developments of hand and eye, the brain correspondingly progressed.

Most of the animals which reached the monkey stage have remained there. These advances appear to have been sufficient for their needs. As fossil and living forms, we find monkeys moderately abundant in the old world. Many are entirely tree dwellers. Some, as the baboons, have descended to the ground, but travel on all fours; many have lost their tails almost completely.

The anthropoid apes.—Almost as soon as the monkeys first appeared in the old world, we find the fossil beginnings of a further development, that of the anthropoid, or manlike, apes. One feature to be noticed in them is an increase in size, an increase which has culminated in the gorilla and man. This, although apparently unimportant, has had far-reaching effects. A small monkey can run along the branches on all fours, but there are comparatively few limbs which a heavy creature can depend on to support his weight. As the size of these apes increased, there was evolved in them a type of locomotion used to a degree by some of the lower primates. While the feet rest upon one limb, the arms grasp another higher one and are used to swing the body from one position to the next. The tail, already small in some of the

monkeys, disappears. Of great importance is the fact that the body is necessarily held more or less upright; erect posture is appearing and with this comes the first possibility of an upright gait on the ground.

The gibbons of southeastern Asia and the adjacent islands are the smallest and most primitive living types of the manlike apes. They do not exceed three feet in height. In many details they still show resemblances to the monkeys. But the power of climbing and swinging upright among the branches is very highly developed in them and the arms are exceedingly long. The gibbon can walk erect using its arms as balancers, but it is an awkward walker; its home is in the trees. The endocranial capacity, that is the space inside the skull filled by the brain and its wrappings, is about 90 cc.[1]

Another rather primitive member of the manlike apes is the orang-utan, the "man of the woods" of Sumatra and Borneo. This is a somewhat larger beast, reaching a height of over 4 feet, and a much more intelligent one. Its endocranial capacity sometimes exceeds 500 cc. But the orang is still a tree dweller; when it walks upon the ground, it does so in a bent position, resting partly on its knuckles at the end of the arms, which are nearly as long as those of the gibbon.

The higher anthropoids; the beginnings of a ground life.—Thus far our primate history has been one of constantly increasing adaptation to arboreal life. But our present knowledge, small as it is, leads us to believe that in the Miocene period a new tendency was beginning, the first traces of a return from the trees to the ground. Three living creatures survive of those ancestral forms in which this trend first appeared. Two forms, the chimpanzee and the gorilla, have not gone far with this process, nor have they met with great success; a third form, man, has succeeded.

[1] We shall give comparable figures for later forms, for this measurement is a rough gauge of mental development. We must, however, take into consideration the fact that the brain varies with the size of the animal although not necessarily in proportion to it.

The great African apes, the chimpanzee and gorilla, are quite similar in many respects. They are larger than any forms previously considered; the chimpanzee reaches five feet or so in height; a male gorilla, six feet at the most. In both, the arms are shorter as compared with the orang-utan or the gibbon, but still exceedingly long by any human standard. Both are quite large-brained; the gorilla's endocranial capacity may run as high as 630 cc. In both, the eyes are buttressed above and behind by strong brow ridges. But in other respects they differ. The gorilla is by far the heavier and more powerful of the two. The chimpanzee is a moderately good walker, either aided or unaided by the hands, but is still essentially a tree-living type. The gorilla, on the other hand, is essentially a ground dweller and takes to the trees only for shelter. The gorilla, perhaps in correlation with its great weight, sometimes as much as 600 pounds, does not normally stand erect, but progresses on all fours on the soles of the feet and upon the knuckles.

We see, then, even in these living forms tendencies which we believe to have been present in an ancestor common to them and to man. Neither of these two great beasts is to be considered as a direct ancestor of man. What do our fossil records tell us of such ancestral forms?

The answer must as yet unfortunately be a very limited and qualified one. In the Miocene and Pliocene rocks of the old world, and chiefly in the Siwalik Hills of India, we find fragmentary remains of large primates. These remains consist of little but teeth and jaws. But teeth are the most characteristic parts of a mammal's anatomy, and the teeth of these creatures have been very carefully studied. Of these fragments we can say that they possess features found today in but three mammals—the chimpanzee, the gorilla, and man. Some of them show characters which tend to make us believe them ancestral to the gorilla or chimpanzee. Some apparently represent short sterile twigs of the anthropoid family tree. And some show tendencies which perhaps lead in a human direction. Beyond this we cannot go. We cannot say defi-

nitely that any known fossil of this age represents the manlike primates from which man took his origin. The fossil record of Asia, however, is still comparatively unknown. It is not only possible, but extremely probable that the Asiatic hills will, upon further exploration, give us the knowledge we desire of the primate ancestor of man.

Human-anthropoid differences.—We have seen the development, through the primate series, of many of man's structures. We have arrived, in the manlike apes, at forms which in almost every characteristic are very close to man. There are still differences, and our attention from here on will be focused upon these, but in doing so the many fundamental resemblances of man and the apes must not be forgotten.

Man is the only one of the higher primates which has really succeeded in the attempt to become a ground dweller. The differences which we may list between modern man and the higher apes are differences which are almost entirely related to the erect gait of man upon the ground and the mental development which seems to have arisen nearly simultaneously.

Modern man stands erect: except for the tiny gibbon, the great apes walk in a stooped position. The arms in man are short as compared with those of any anthropoid ape; they are no longer used in walking or swinging among the boughs. With the release of the arms, the hands come into their own. The thumb, which tends to be small in the manlike apes, is enlarged; the hand is a versatile grasping organ, while the grasping big toe of the monkey and ape is reduced and comes into line with the other toes.

Even in the highest of the apes there is something of a "muzzle" to accommodate the powerful teeth. In man the tooth row has been shortened, partly, it would seem, in relation to his diet. As the teeth have retreated, the face has become more nearly vertical, and the end of the jaw is left as the "chin." In the higher manlike apes heavy ridges are found above the eyes in front of the low forehead. In man, as the brain grows and the vault of the skull increases, these ridges tend to disappear.

But it is in the brain that the greatest contrast between the apes and man is to be found. We have noted the increased importance of the cerebral hemispheres in mammals in general, as compared with all lower types. Through the primate series this advance has been continued. But here, at the end of the series, this growth has been greatly accelerated. The cerebrum, and with it the higher functions of which it is the seat, has increased enormously. The endocranial capacity of the average reader is about two and a half times that of the highest of living apes. And practically all of this increase is due to the growth of the cerebrum and parts related to it.

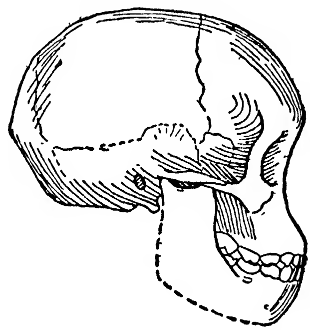


FIG. 102.—The skull of the "southern ape," *Australopithecus*. (After Broom.)

We have recounted some of the differences between the highest living apes and the modern type of man. We must remember, however, that these differences are, except brain growth, of a comparatively insignificant nature, as contrasted with the differences between many other types of animals. And it must be borne in mind that these differences did not arise in one swift change. They were slow in their development; and our fossil remains of manlike creatures, poor as those records are, show us some of the stages in this evolutionary process.

The "southern ape." (Fig. 102.)—Very recently there has been discovered in South Africa part of the skull and an impression of the cranial cavity of an ape to which the name *Australopithecus*, or "southern ape," has been given. The remains are those of an ape "child," corresponding in age to a human child of six or seven; and we must be careful here, for the skull of the young chimpanzee or gorilla is much more human than that of the adult. But, even with due allowance for this fact, it is claimed that we have here the remains of a very advanced ape, one which was in brain development and other respects close to, although not quite reach-

ing, the lowest human level. A full description of the specimen has not as yet been published; but it seems probable that we have here a very close relative, at least, of the anthropoid type from which man has come, although the probable late date of the specimen (Pleistocene?) places the creature at too late a time for it to have been the actual ancestor of man.

The Java "ape-man."—In the nineties there were discovered near the village of Trinil, in Java, fragments of the skeleton of a manlike creature (Fig. 103). The deposit dates from a time just before or just at the beginning of the Pleistocene. The remains consist of the top of the skull, three teeth, and a thigh bone. What do they tell us?

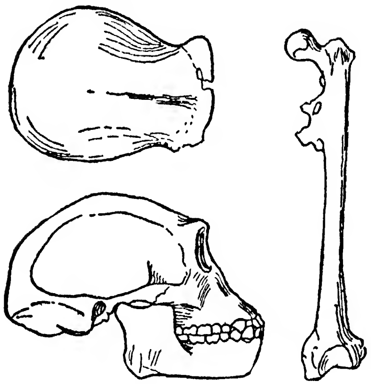


FIG. 103.—The skull cap and thigh bone constituting most of the known remains of the "Java ape-man," *Pithecanthropus*, and Dubois' original restoration of the skull. (After Dubois.)

The size of the thigh bone indicates that the creature was of human size. Its shape indicates that it walked erect. The teeth resemble most nearly those of man. The top of the skull indicates that the brain was larger than that of any known ape, although much below high human standards. The forehead is exceedingly low for a man, and the ridges above the eyes are massive as compared with those of any known man, although smaller than those of most apes.

Where does this creature rank? Is it a true "missing link," as its discoverer at first thought, and hence deserving the name, *Pithecanthropus erectus*, "the erect ape-man"? Or is it merely a large ape? Or is it a man of an exceedingly early and primitive type?

Recently published work shows the last surmise to be the most probable one. The interior of the skullcap has been de-

scribed. The endocranial capacity has been estimated with a high degree of probability, at little over 900 cc. This is 300 cc. greater than that of the gorilla; but it is 400 cc. lower than that normally found in any "lower" existing races of men, and 600 cc. below the European standard.

From a cast of the interior of the skull we can reach further conclusions. The frontal portion of the brain, in the development of which modern man differs greatly from that of any existing ape (see Fig. 129), is comparatively small. But, on the other hand, those parts with which it is believed that speech is associated are already developing. It is reserved for a later chapter to discuss the tremendous effect which speech has had on human progress. Combined with the presence of other human characteristics in *Pithecanthropus*, the probable possession of speech leads us to conclude that we already have in this creature a being that is man, of a sort, rather than an ape.

Had the use of tools already begun at this stage? We cannot surely say. The hands of *Pithecanthropus* are unknown. Since they were freed from locomotor necessities, it seems probable that they were at least approaching human form; the brain of this creature seems certainly well up toward a condition in which the use of tools might have been attempted. Tools of soft material, such as wood, would not be preserved; our oldest records of human tools are chipped stones. No traces of human handiwork have been found associated with *Pithecanthropus*. At about the same age, however, flints are found in England which, it has been suggested, were used by man; but this belief is not shared by all.

The Pleistocene glaciation in Europe.—From this time on, the scene of our discussion shifts for the most part to Western Europe. In the new world, as we have said, there is no trace of man previous to the coming of the Indian. From time to time reports of the finding of ancient human remains in this country have been made, and probably will continue to be made, but in no case has such a finding been confirmed. Man, it seems, was an old-world

product. And in the old world the only portion which has been at all carefully explored is civilized Western Europe.

This is unfortunate. During the historical period Western Europe has not been the home of the races which we find as the successive inhabitants or conquerors of this region. Wave after wave of invasion has swept over it, bringing in new races from the east or south. We believe this same condition to have prevailed in much more ancient times. The history of these last stages in the evolution of man must be based on evidence gathered in a region far from that in which the main events of the story were occurring. Man quite certainly did not evolve in Europe; the extinct races which we find there are migrants from a center of evolution which lay elsewhere, be this central Asia, as is commonly supposed, or possibly Africa.

It has been said in a previous chapter that great glaciations have occurred at intervals throughout geological history. The last of these glacial periods occurred during the Pleistocene, the geologic period just behind us. In Europe there seem to have been four successive "peaks" of this glaciation. Four times the glaciers advancing from the Alps, from Scandinavia, and from other centers, covered much of Europe, accompanied by colder temperature over the adjacent regions; four times they retreated, giving three interglacial periods, and finally the comparatively short post-glacial times in which we are now living.

The glaciations help in giving us certain time-markers for dating our material. For example, the glacial stages were times when moist climates prevailed. Rivers were swollen and became active agents of erosion, and consequently deposited great accumulation of sand and gravel along their lower courses. With the coming of an interglacial stage deposition would cease, the streams would begin to erode and only terraces of the former filling would be left. Then, with the next great glaciation, valley bottom deposits would again be formed, but (since the river had cut deeply during the interglacial epoch) the new floor would be lower in the valley than the terrace remnants of the earlier filling. The new filling, in

turn, might be trenched and terraces left. In this way remains found in river terraces may be dated; the oldest in the higher levels, the youngest in the lower.

In other ways our purely geological knowledge helps us in dating remains. Toward the end of the period, especially, the successive deposition of earth and included remains in caves gives us assistance of great importance. This type of investigation will be described in the next chapter.

The animals and plants are of the greatest use in dating the remains of man. During the Ice Age, old types of animals, such as the saber-tooth tiger and the mastodon (a primitive relative of the elephant), were dying out, and other types gradually evolved. With each advance of the ice, tropical and temperate plants in central Europe gave way to pine forests and the small plant life found today in the far north or alpine regions. Southern types of elephant and rhinoceros migrated southward, and were replaced by hardier relatives from the north and east; and the same type of change could be recounted in many animal types. If, then, we find remains of animals or of plants, we can determine fairly accurately whether our find is from an early or late part of the period, and whether the deposit which contains it was laid down during or between glaciations.

The "dawn man" of Piltdown.—Near the manor of Piltdown, in Sussex, England, are to be found river gravels, which are often used as road-making material. The remains of animals contained in these gravels do not enable us to say certainly when they were deposited there; perhaps they are as early as first or second interglacial times. Less than a score of years ago the remains of a manlike being were discovered in them, but it was badly broken and scattered by the workmen's picks. Pieces composing the greater part of the skull and jaw were collected; careful search has since revealed a few other fragments. The skull, as fitted together and restored (Fig. 104), tells us that we are dealing with a manlike rather than an apelike type; and the creature has been named *Eoanthropus*, the dawn man. The cranial capacity was about

1,300 cc.; that is, far greater than that of *Pithecanthropus*, up to the average of existing races, but still short of that normally found in Europeans today. Here, as in *Pithecanthropus*, the speech centers are developed; but again, like *Pithecanthropus*, the brow region of the skull is low and the frontal part of the brain is small.

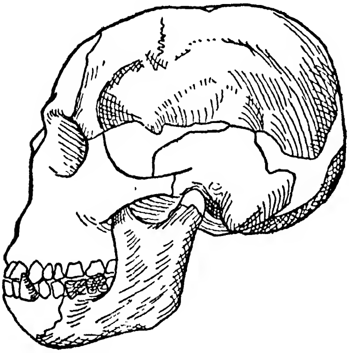


FIG. 104.—Side view of the skull of the Piltdown man, *Eoanthropus*. The unshaded portions are restored. (After Elliot Smith and Hunter.)

The jaw is of another nature. (It will be remembered that no jaw was found with the Java "man.") This is exceedingly apelike, chinless, and with many features suggesting such an animal as the chimpanzee. It has been suggested that the skull and jaw do not belong together; that the skull is truly that of a primitive manlike creature, but the jaw that of a chimpanzee. On the other hand, no chimpanzees are known in Europe during the Ice Age, and this renders the theory somewhat improbable. An apparently clinching piece of evidence was the later discovery, about two miles away, in the same gravels, of a fragment of a second skull, and associated with it a tooth of the type of that found in the original jaw. That the chance association of a human skull with the jaw of an otherwise unknown ape should have happened once is possible; that it should happen twice is exceedingly improbable. The development of human mentality in all probability was under way before the evolution of the human type of jaw and face.

The Heidelberg jaw.—Near the university town of Heidelberg, in Germany, some twenty years ago, in sands laid down during the first or second interglacial period, was found another human fragment, in this case a jaw (Fig. 105). The teeth are distinctly human in type rather than apelike. The jaw itself, however, is very powerful and has many primitive features; the human de-

velopment of the "chin," for example, is lacking. Perhaps this Heidelberg "man" was an ancestor of the next form to be considered, but this is uncertain.

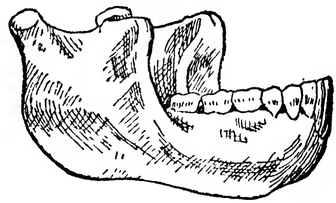


FIG. 105.—The Heidelberg jaw. (After Schoetensack.)

The last of the lower types—Neandertal man.—In the third interglacial stage, implements tell us unquestionably of the presence of man in Western Europe. Then, as the last of the four glaciations commenced, we find in caves and rock shelters comparatively numerous remains of an ancient type of manlike creature below our own level of which we can speak accurately respecting the structure of all parts of the skeleton.

The cranial capacity is well up to modern human standards (being on the average 1,500 cc.). But in the proportion of the parts of the brain we find a great difference from that of our own species of man. The frontal area, for example, is small, in contrast to other areas. The forehead is still low; great brow ridges are to be found above the eyes. The face is projecting, the "chin" retreating.

The creature walked erect, but not perfectly, for there was still a slight apelike stoop to the body; the knees were habitually somewhat bent; the large hands still lacked the perfected opposability of our thumbs. We have here a member of our own genus, *Homo neandertalensis* (Neandertal man). He is a man, in a broad sense, but a man with the mark of the ape still upon him. And further, certain of his characteristics show that he himself is probably not ancestral to our own kind, but rather that he and our own species had a common ancestor, of Asiatic (or African) origin.

The coming of true man.—At the beginning of the last glaciation we find Neandertal man in possession of Western Europe. But toward its close we find a new type of man entering Western Europe and apparently taking over the land from the

Neandertal people. In the new races (the Crô-Magnon and others) which now entered Europe we see for the first time man essentially as we know him today. The brain is of the true human type. Gone are the great brow ridges, the low sloping forehead. The teeth no longer project in apelike fashion; the "chin" is developed. The body is truly erect; the limbs are of truly human pattern. Man, true man of our own species, is here. With this our story of man's evolution from his vertebrate ancestors ceases. The remainder of the story is the evolution of *Homo sapiens*.

We have witnessed the rise and fall of many great groups of vertebrates. We have seen the great reptiles flourish for many millions of years, only to die out and be succeeded by the mammals. Today we are witnessing the triumph of man over these animals in turn.

What will the future bring us? Will some other type of creature arise to supplant us, as we have supplanted our mammalian relatives? Or is something better, something finer, to come from man himself?

SELECTED REFERENCES

1. R. S. Lull, *Organic Evolution* (The Macmillan Company, 1917).
2. H. H. Newman, *Vertebrate Zoölogy* (The Macmillan Company, 1920).
3. H. F. Osborn, *The Origin and Evolution of Life* (Charles Scribner's Sons, 1923), chaps. vi–viii.
4. H. F. Osborn, *Men of the Old Stone Age* (4th ed., Charles Scribner's Sons, 1918).
5. W. B. Scott, *A History of Land Mammals of the Western Hemisphere*, 1913.
6. G. Elliot Smith, *The Evolution of Man*, Essays (Oxford University Press, 1924).
7. H. H. Wilder, *History of the Human Body*, 2d ed., 1924.

CHAPTER XII

THE COMING OF MAN

FAY-COOPER COLE

I. PREHISTORY OF MAN

In the preceding chapter we have seen the development of the vertebrates and the manlike beings, as revealed by the fossils of *Pithecanthropus erectus*, Heidelberg man, and Piltdown man.[1] Up to this time, however, our manlike forms are few in number, are widely scattered, and are separated by thousands of years. But with the coming of Neandertal man the situation changes, and from that time on human development is presented as a continuous story. The evidence is both skeletal and cultural and must be considered in relation to the time sequences established by the geologist and paleontologist.

For the purposes of our discussion we shall deal with Europe, since it is the best-known region archaeologically, and it is there that the most careful correlations between cultural and geological periods have been established.

The glacial epochs.—Geologists tell us that, toward the end of the Tertiary Period, Europe enjoyed a warm climate and that tropical plants and animals existed in the land. Then slowly a great ice sheet formed in the far north and pushed south out of Scandinavia and well into what is now Germany. With the advance of the front of the northern ice sheet, minor glaciers formed in the Alps and Pyrenees and spread down into France and Spain, until finally considerable portions of Europe were covered.

With the change in climate many of the tropical plants and animals were destroyed or retreated toward the south and were replaced by the flora and fauna of the north. It must be remembered, however, that during each of the glacial epochs there were sections of Europe which remained free from the ice and that in

[1] Between 1927 and 1929 there were found near Peking in China skulls, teeth, and other portions of some ten individuals. The associated animal life dates them as belonging to early Pleistocene. These beings, known as *Sinanthropus*, are a step above Pithecanthropus, yet are exceedingly primitive.

CHART III

Chronology of Paleolithic Times in Europe

	GEOLOGICAL EPOCHS		ARCHAEOLOGICAL EPOCHS	RACE OR RACES
	Recent		Neolithic and Modern	Modern
POST GLACIAL	Daun Gechnitz Bühl	PALEOLITHIC (OLD STONE AGE)	Azilian-Tardenoisian	Transition to Modern
			Magdalenian	Crô-Magnon
			Solutrean	Crô-Magnon and (?) Brünn
PLEISTOCENE (OR GLACIAL PERIOD)	Würm Glaciation		Aurignacian	Crô-Magnon and Grimaldi
			Mousterian	Neandertal
	Third Interglacial		Acheulian	Neandertal (?)
			Chellean	Neandertal (?)
	Riss Glaciation		Pre-Chellean (?)	Piltdown (?) (Perhaps earlier)
	Second Interglacial			Heidelberg
	Mindel Glaciation		Eolithic (?)	
	First Interglacial			
	Günz Glaciation			Sinanthropus (In China)
	Tertiary Period		Eolithic (? ?)	Pithecanthropus (In Java)

these regions there was considerable mingling of the life of north and south.

After a period of tens of thousands of years the glaciers retreated, and Europe again enjoyed a balmy climate while the warmth-loving African-Asiatic animals returned to their former haunts. Four times this was repeated, and four times did the shifting life of north and south pass over the land. This record of Europe during the ice ages can now be read in many places where excavations or sheer cliffs expose the strata of the rocks. The courses of the glaciers have been mapped and the associated plant and animal life studied, until it is possible to date one stratum in relation to another with a high degree of certainty.

Eoliths.—In the strata laid down during the First and Second Interglacial epochs are found many chipped flints and other stones which appear to have been intentionally shaped. There is no uniformity to these flints; some may have been used as cutters or scrapers but others are so crude or of such peculiar shapes that it is unlikely that they could have served any human purpose. The name eoliths, or dawn stones, has been applied to these early forms which may have been made by man, but many archaeologists are inclined to doubt the authenticity of many of these objects. These doubts are further strengthened by the knowledge that similar forms may be the accidental products of nature—the results of pressure, of heat and cold, and other factors—and by the fact that similar stones are to be found in much earlier strata, even of the Middle Tertiary, before we have evidence that man or his near relatives had appeared.

It is probable that many of the flints belonging to the Second Interglacial epoch were used by man, but since there is question we shall take the conservative view and make no positive claims for human artifacts until the Third Interglacial.

The Chellean epoch.—Soon after the retreat of the Riss Glaciation, man certainly was in the land. We have no skeletal remains for this epoch, but scattered over southern England, Spain, France, Germany, and even farther to the east, are thou-

sands of stone utensils concerning the intentional manufacture of which there can be no doubt.

In western Europe the typical artifact of this time was the *coup de poing* or hand axe, made by striking off large flakes of flint until the core or nodule itself formed a crude wedge-shaped axe, or pick, with jagged edges. The top was usually left unfinished or was pounded flat so that it could be held in the hand. It was a crude but effective device and for thousands of years it

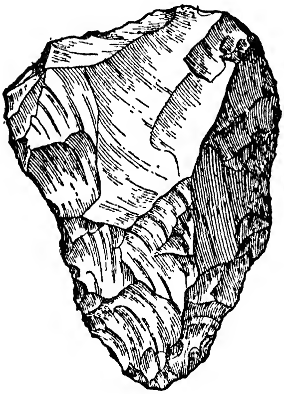


FIG. 106.—Chellean handaxe (*Coup de poing*).

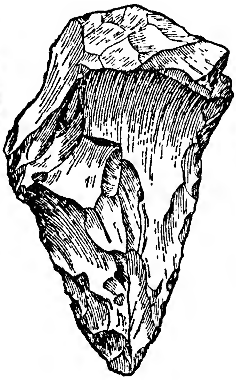


FIG. 107.—Chellean handaxe (*Coup de poing*).

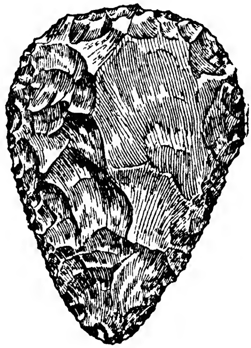


FIG. 108.—Acheulian axe.

served as the chief weapon and tool of man. The epoch in which the *coup de poing* was predominant is known as the Chellean, from the type station found by Mortillet in 1887, near the village of Chelles in northern France. Doubtless man of this period had other utensils, probably of wood, but he was then a hunter living in the open and hence nearly all other evidences of his occupancy have vanished.

The Acheulian epoch.—During the Chellean epoch some advance was made in stone utensils, but about the middle of the Third Interglacial there was a marked development in flint work. The process is the same, the *coup de poing* remains, but the chipping is finer, more even, and the top is finished off, suggesting that

it is no longer held in the hand but is hafted to form a true axe. There also appear many smaller utensils of similar type which may have served as skin cleaners or even as drills. The type station for this advanced culture was excavated near St. Acheul in the valley of the Somme in northern France, and hence the period is called Acheulean.

Thousands of Acheulean utensils have been found, chiefly in valley deposits, but we have no human remains sufficiently well preserved to tell us with certainty the race of man which existed at that time. It is probable, however that Neandertal man occupied Europe during the Chellean and Acheulean periods, for we find him in possession in the succeeding epoch with a culture that offers no sharp break from the preceding.

In late Acheulean times a marked change in climate took place. The country became semiarid, the forests changed or vanished, and many of the tropical animals, such as the hippopotamus (*Hippopotamus major*) and southern mammoth (*Elephas meridionalis*) gave way to more northern forms. But there was considerable mingling of the faunas of north and south, and man was still able to live in the open.

The Mousterian epoch.—With the advance of the Fourth Glaciation there was a change to cold, moist conditions, and many new animals appeared, among them the woolly rhinoceros (*Rhinoceras tichorhinus*), the woolly mammoth (*Elephas primigenius*), the arctic fox (*Canis lagopus*), and the reindeer (*Rangifer tarandus*). Man was compelled to seek the protection of the caves and rock shelters, and here for the first time we are able to study early home life in Europe. The new conditions gave less freedom of movement. Man was still a hunter, but the number of natural shelters was limited, and, once a group was in possession, it apparently remained until dispossessed or until the necessities of the chase caused its voluntary movement.

Near the entrance of the cave the inhabitants built their hearths, here they divided the game, here they cooked the flesh and broke open the larger bones to secure the marrow, and hav-

ing finished their repast, they threw the refuse to one side. Here, too, they brought nodules of flint and by the light of their fires or flickering torches they fashioned their tools. Broken or discarded utensils were left with the refuse from the flint chipping and occasionally a good specimen was lost in the débris. Ashes from the fires were pushed to one side, covering the remains of the meals and the chippings of the tool-makers, and so, slowly through the years, the dwellers in the caves unconsciously established a record which now reveals to us many of the details of their lives. By

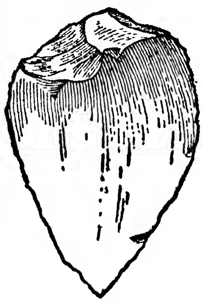


FIG. 109.—Mousterian point showing use of flake.

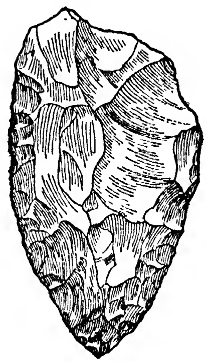


FIG. 110.—Mousterian point showing chipping.

making a careful study of these refuse heaps we know the sort of game they hunted, we know how they made their utensils, and we find their first attempts to utilize bone in place of stone. Of even greater importance is the fact that they buried their dead together with their crude instruments, so that we are not in doubt as to the sort of man that inhabited Europe during most of the fourth glaciation.

This epoch is known as the Mousterian from the caves of Le Moustier in southern France. Culturally it was at first a continuation of the Acheulean. The *coup de poing* and smaller utensils were still in use, but soon a new method in stone-working made its appearance and finally replaced the old. Instead of striking off

chips until the nodule could be used as a weapon, the worker in the new process knocked off a large flake and shaped and sharpened it by secondary chipping on one side. In appearance it was a cruder implement than that of typical Acheulean times, but the new invention made possible many new forms and small utensils, some of which may have been employed as blades when held between the thumb and forefinger, while some may have been mounted in shafts and thus served as spears or daggers.

Neandertal man.—Of special interest is man himself. He is known as Neandertal (*Homo neandertalensis*) because of the finding of the first complete skeleton of this type in the valley of that name in western Germany in the year 1856. So unlike modern man was this first specimen that even Virchow, the great German pathologist, pronounced it a monster, a pathological human being. But since that time more than a score of these burials have been uncovered and we have skeletons ranging from children to adult men and women. It is now certain that we are dealing, not with abnormal individuals, but with members of a distinct species of man who at one time occupied much of Europe; while recent finds in Rhodesia and Palestine indicate that he may have extended far into Africa and beyond the eastern end of the Mediterranean.

The men were about five feet three inches in height, the women four or five inches shorter. They had long, rather narrow and low heads with huge bony ridges above the eyes. Back of the ridge the forehead retreated abruptly, indicating little development of the anterior portion of the brain, but the occipital region was so expanded that the average cranial capacity was around 1,550 cc., or slightly in excess of that of modern man. The nose was broad, the upper jaw projected forward resulting in a long upper lip. The lower jaw was massive and indicates huge muscles of mastication, but there was little or no development of chin. The foramen magnum, the opening through which the spinal cord enters the cranium, was situated farther back than in modern man, and this, together with the points of articulation of the skull with the

bones of the neck, shows that the head hung habitually forward on the chest. The skeleton proves that these people were short but massively built, with arms long in proportion to the legs. In all cases we find that the thigh bone is curved and this, together with the muscle attachments, shows that Neandertal man walked in a semi-erect position. We have here a true man, but one much more apelike than any existing race. In fact he differs more from all the existing races than these do from one another. Because of these facts and because there is no proof that he is ancestral to present man he is considered a distinct species and is called *Homo neandertalensis*.

All Neandertal skeletons found in Europe have been associated with artifacts of the Mousterian period, and with animals which flourished during the Würm Glaciation. Hence there can be little doubt but that these people were the principal if not sole occupants during most of the time that the last great ice sheet existed in Europe. We have already seen that they may have been the occupants during the two preceding epochs.[1] These three epochs —the Chellean, Acheulean, and Mousterian—show slow but steady advance in stone utensils and we may suspect a parallel development in more perishable materials, but the known culture is still exceedingly crude and is so far below that which followed that they are generally called the Lower Paleolithic.

Appearance of Crô-Magnon man.—With the waning of the Würm Glaciation a cold dry climate prevailed; steppe lands covered great areas, while the arctic lemming (*Myodes torguatus*) and Asiatic mammals, such as the kiang or wild horse (*Asinus hemionus*) came in great numbers. Of much greater importance, however, was the appearance of a new race of men. These newcomers, known as Crô-Magnon (from the rock shelter of that name near Les Eyzies in southern France) so closely resemble man of today that they are classed in the same species as ourselves, *Homo sapiens*.

We can describe Crô-Magnon as straight of limb, with an average height for the men of nearly six feet, the women con-

[1] Recent finds in undisturbed strata near Rome and at Ehringsdorf, Germany, make it certain that Neanderthal man was in Europe during third interglacial times

siderably shorter. The head was long, narrow, and high, giving a cranial capacity slightly in excess of that of modern man. The forehead was full and smooth; there was little forward projection of the upper jaw, and the chin was well developed. The cheek bones, however, were unusually wide, making the face appear disharmonic.

It is thought that Crô-Magnon man probably underwent a long period of development somewhere in Asia, and entered Europe with all his physical characteristics fully established. There is no reason whatever to consider him as a development of, or closely related to, Neandertal man. He appears as an invader and soon replaces the earlier inhabitants. His main route into Europe has been traced along the southern shores of the Mediterranean and across the land bridges, which then existed at Italy and Gibraltar, and thence into western Europe.

The Grimaldi race.—While Crô-Magnon man was dominant in Europe he was not the sole occupant. In the Grimaldi caves, near Mentone, Italy, was found an early Crô-Magnon burial place and almost directly below it another interment. The nature of the burials, the articles placed with the dead, and the associated animal remains indicate clearly that the two graves belong to approximately the same period, but the lower contains the bodies of a woman and boy which show distinct negroid characteristics. It appears, then, that we have in Europe at this time representatives of two highly specialized groups, one of which seems to be closely related to the present Caucasoids, the other to the Negroids.

The Upper Paleolithic.—With the appearance of Crô-Magnon man we enter the Upper Paleolithic. This is further subdivided into three cultural epochs, named for sites in France in which the type was first studied. The first is known as Aurignacian, from a small cavern near Aurignac in the Pyrenees of France; the second is the Solutrean, from Solutre in southern France; and the third is Magdalenian, from a grotto, La Madeline, in the Dordogne valley. These cultural epochs are related in a way to geological

epochs. The Aurignacian corresponds in general to the retreat of the Würm glacier; the Solutrean to the relatively mild period following the retreat; while the Magdalenian extends over three minor glaciations, known as the Bühl, Gechnitz, and Daun (Chart III).

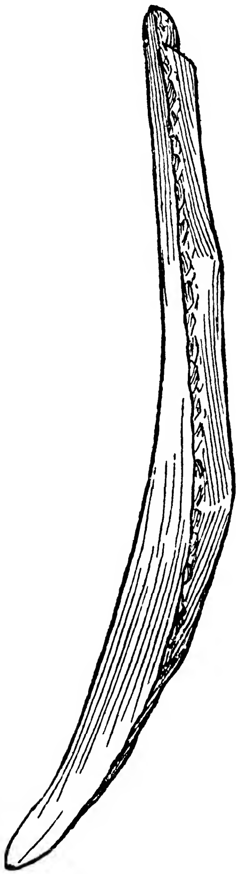


FIG. 111.—Aurignacian end scraper.

Aurignacian epoch.—The Aurignacian began with the entrance of Crô-Magnon man and extended over western Europe until superseded by the Solutrean, but in the south it continued unbroken until the Magdalenian. Culturally it marks a great advance over the Mousterian. Artifacts of the earlier period still appear, but the typical stone utensils were made by striking long narrow blades from a prepared nucleus and then finishing the edges by secondary chipping. The work was not fine, but allowed for a great variety of tools—scrapers, blades, chisels, gouges, and many small points probably employed as engraving tools. The greatest advances, however, appear in bone. Here we meet with bone javelin or spear heads, needles, awls, wedges, rods of peculiar type which may have had magical uses. Necklaces and bracelets of bone, teeth, and shells appear, also tubes filled with red ochre possibly for body painting. In this period we also find the beginnings of the art which stands as the most remarkable achievement of Crô-Magnon man.

Solutrean epoch.—During Aurignacian times man still made his home in the shelter of the rocks, but in the interval between the Würm and Bühl glaciations he lived in the open. At this time there appeared in central France, Belgium, Germany, Poland,

and old Austria-Hungary new types of chipped implements which varied so radically from those found in the preceding or following epochs that it has been suggested that they may be the products of an invading people, who for a time superseded the Crô-Magnon. In Czecho-Slovakia there have been found human remains, belonging to this epoch, which bear some resemblance to both Crô-Magnon and Neandertal, but which may be distinct from either. This type is called the Brünn race and it is possible that they may have been instrumental in introducing the new culture, but if so their supremacy in Europe was brief and their influence limited.

In this epoch, known as the Solutrean, stone work reached the greatest perfection of Paleolithic times. Long blades, resembling in outline the laurel leaf, were delicately retouched on both sides by the pressure method until they were remarkably thin (Fig. 112). Some were provided with a lateral base notch, probably for fitting into a shaft to make a knife or javelin. Judged by its flint work this was a period of great advance, but bone utensils are few and of inferior workmanship, while art received a decided setback.

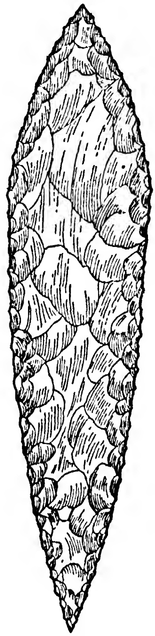


Fig. 112


Fig. 113

Figs. 112–113.—Fig. 112, Solutrean laurel leaf point. Fig. 113, Solutrean point showing lateral base notch.

Magdalenian epoch.—With the advent of the Bühl Glaciation we enter the Magdalenian epoch. Because of the cold, man was compelled to spend at least a part of his time in caves and shelters, and the evidence left about his hearths tells us that he had given up almost entirely the flint work of the Solutrean period and had returned with little change to that of the Aurignacian. Long, narrow flint blades and gravers reappear as the typical stone imple-

ments. Bone harpoons with detachable barbed heads, the harpoon thrower, and bone lance heads show marked development in weapons of the chase, while delicately shaped needles and bone

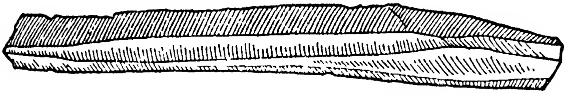


FIG. 114.—Magdalenian scraper

plugs, shaped somewhat like collar bottons, suggest the possession of skin garments. Ornaments of bone, shell, and teeth become very common, while hammers and chisels of bone, flutes, and whistles, and objects of problematical use indicate a very highly developed culture, one which in many ways approximates that of the present-day Eskimo.

There is some question as to whether man of both Aurignacian and Magdalenian epochs is to be classed as Crô-Magnon. Aurignacian man was of greater average stature and cranial capacity, and of sturdier build, but otherwise there is little difference between the skeletons of the two epochs. If we allow for the effects of environment and some possible admixture in Solutrean times we probably can account for such variations as exist. We have already seen that the culture is much the same, but that of the Magdalenian is so far in advance of all that preceded that it may be termed the golden age of Crô-Magnon man.

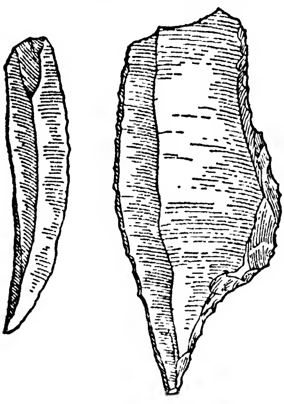


FIG. 115.—Magdalenian awl and drill.

The art of Crô-Magnon Man.—Great as were the developments in all lines, that in art was the most noteworthy. Beginning with simple outline sketches, the Crô-Magnon artists perfected their work until, in Magdalenian times, they were engraving, painting, and modeling lifelike figures of the animals which they were hunt-

ing. Sometimes the sketches were on weapons and utensils, but more frequently the artists of long ago made their sketches on the walls far back in the recesses of the caves. There they cut and painted and modeled figures of bison, mammoth, and many other animals now extinct in Europe. It is probable that this art, like that of many primitive tribes of today, was produced with the idea that, when proper ceremonies and acts were made before the figures, the animals represented would be magically compelled to increase and be easily taken.

Sculpture first appears in Aurignacian times but is confined to small figurines, usually representing women of the Bushmen-Hottentot type. It has been suggested that they may have been introduced into Europe from Africa, but whatever the origin, they were widespread in this period. It is probable that they were connected with magical and religious rites intended to promote fertility.

In Magdalenian times many small animal figures were carved in bone and ivory, but most remarkable were the animal figures modeled in clay or cut in high relief which have been found in several caves in France. These represent bison, horses, and bear, some of them showing wounds inflicted by darts. These figures, like the paintings and line drawings, show great ability in depicting the most essential details of the animals, both in action and at rest; and this, despite the fact that they must have been produced from memory or from sketches. Here, again, we have proof of the great potential ability of Crô-Magnon man. In many ways he advanced far, but he was still a hunter without knowledge of domestic plants or animals, without pottery, writing, and many other elements of our civilization.

The period of transition.—With the final retreat of the ice, great changes occurred both in flora and fauna. The reindeer, bison, and mammoth disappeared and were replaced by deer and other animals typical of the early European forest. For man it was a period of transition. He still spent some of his time in the caves, but he also made camps in the open. The prevailing type of stone work consisted of pygmy flints in geometric forms; bone

work was represented by crude harpoons and wedges; while the highly developed art of Magdalenian times degenerated into crude markings on pebbles, or line drawings of human beings, sometimes in groups, sometimes on the hunt. In these figures we get the first hint that the bow and arrow had come into use and that it was being employed both in the chase and in warfare.

This period of breakup and change is usually known as the Azilian-Tardenoisian from the two type stations, Mas-d-Azil in the foothills of the Pyrenees, and Fère-en-Tardenois in northern France. During this period Crô-Magnon man disappears. Some students think he was absorbed or exterminated, while others believe he followed the reindeer to the north, there to become merged with such groups as the Eskimo. At all events, he vanishes from Europe as a race.

It is probable that the ancestors of the present races were beginning to push into Europe at this time. Apparently they did not come as a great invasion but as small bands which penetrated farther and farther toward the Atlantic. From the regions to the east of the Mediterranean came the ancestors of the Mediterranean race; over the lower passes of the Alps came the Alpines; while the Nordics forced their way into Scandinavia by following the shores of the Baltic and North Seas.

The Neolithic period.—The culture of these early comers was very crude; they dwelt along the banks of streams and lakes and subsisted chiefly on shellfish and game. Slowly the shells and bones accumulated around their settlements until they formed great heaps, known as kitchen middens. Other settlers built their villages on piles out over the water and the débris collected beneath their houses until often it made layers of considerable thickness. Today a study of this refuse reveals much concerning the life of this people. We know that at the time of their entrance into Europe they were in possession of the bow and arrow and were just beginning to make crude pottery. They still made use of the flaked utensils of the Paleolithic periods, but in addition they possessed implements, the edges of which were ground or

polished. Later they came to polish the whole surface of their more important utensils, and hence the period has received the name Neolithic, or New Stone Age, or Age of Polished Stone. The dog appears, first as a camp follower, but soon becomes the constant companion of man; other domestic animals follow, and soon we meet with the first evidences of domestic plants. From then on changes are rapid. With domestic plants and animals, man becomes attached to a locality. He had something to defend and, in order to preserve his holdings, he doubtless was willing to subordinate himself to authority and so, apparently, village life developed. Then, slowly, the inventions of the great nations of antiquity, of Egypt, Crete, Mesopotamia, and lands of the East began to penetrate into Europe. First came the knowledge of copper, then of bronze, and finally of iron.

The limits of this chapter will not permit a full discussion of these later periods. It should be noted, however, that in the more favorable regions, in the valleys of the Nile and the Euphrates, civilization developed much more rapidly than to the north. Contacts of people, through war and trade, tended to break down conservatism, and progress was so rapid that prior to 2500 B.C. great empires had arisen, engineering projects of considerable magnitude were undertaken, writing was developed, while astronomy and mathematics received much attention. In addition to all this were highly developed religious systems which profoundly influenced the trend of these civilizations. Some elements of this advanced culture spread through trade, but it was not until the invading armies of Rome began to push into Gaul that central and northern Europe came into full contact with the progress of the south.

The accompanying chart (Chart III) gives in outline the prehistory of Europe, as we have sketched it, from the entrance of Neandertal man up to the coming of the modern races.

The nature of the evidence.—We may now consider the sort of evidence on which such an outline is based. In many places there are caves and rock shelters where this record can be read

very much as the geologist interprets the history of past ages from the strata of the rocks. A single example will be given here.

Near Schaffhausen, Switzerland, close to the Rhine, is a rock shelter which in historic times had often been occupied by gipsy bands. Scientific exploration of the site was undertaken in the hope that it might give evidence of habitation in prehistoric times.

In order to take advantage of any stratification which might be evident, a preliminary trench was run from front to back and was carried down to the floor of the cave. Five levels, or strata, varying from thirty to eighty centimeters in thickness were exposed in the following order:

1. At the top—recent dark soil containing bones of wild and domestic animals of the historic period. Mixed with these were objects lost or discarded by the campers—a ring, bits of glass, buttons, some objects of iron, a few pieces of bronze of pre-Roman date. Judging from the material objects, as well as from animal and plant remains, it is safe to assume that this layer was entirely deposited within the historic period.

2. Next below was a deposit containing such quantities of ash and charcoal that it was termed the "grey layer." An ancient hearth was discovered, and scattered about it were the bones of animals which had served as food for the inhabitants. Careful identification has shown these to be animals which roamed Europe at the end of the glacial period. That this is correct is further shown by the fact that many of the stone utensils have their surfaces ground and polished, while an abundance of pottery gives further proof that this layer accumulated while Neolithic man occupied the shelter.

3. Directly below this is a layer eighty centimeters in thickness, built up almost entirely of fragments which have broken away from the overhanging cliff and of remains left by thousands of rodents. In a few places there are signs of fire, but otherwise this stratum is sterile so far as human remains are concerned.

4. Beneath this is a layer containing thousands of bones of reindeer, bison, and other animals which lived in Europe during

the Magdalenian period. Many of these bones have been fractured to obtain the marrow for food. Bone utensils and stone work of late Paleolithic type are found in great abundance, but polished stone and pottery are entirely lacking.

5. Next comes another rodent layer, but included in it are some utensils, probably of Mousterian age, and animal remains typical of the latter part of the Würm glaciation.

Still further to complete the proof, this lowest stratum lies on the gravels of a terminal moraine which, according to the geologists, was probably deposited by the Würm glaciers.

All material from the shelter was removed, layer by layer, and put through sieves of various sizes. Each object of human manufacture, as well as animal bones, was labeled and sent to experts for identification.

This is but one of many sites in which careful excavation has demonstrated distinct stratification, by means of which the correlation of archaeological and geological periods has been established. In some cases human skeletons have been found, thus further completing the record.

Summary of prehistory.—We have now traced the story of man in Europe from the first positive evidence of his occupancy up to the coming of the modern races. Neandertal man was found to be distinctly human, but he still retained many features which place him closer to the common ancestor of man and the anthropoids than are any of the later races. He shows marked development in cranial capacity over the earlier fossil forms, but in configuration of skull he offers no sharp break from *Pithecanthropus erectus*, while his mandible—or lower jaw—is much more like that of Heidelberg man than is found in any of his successors. He is replaced by an invading people, Crô-Magnon, and they, in turn, give way before the incoming Neolithic races.

The story of man in Europe cannot, then, be told in terms of one race or even of one species. It is a record of invasions, long occupancy accompanied by slow cultural changes, and sudden replacement by entirely new races.

On the cultural side, the material at our command tells us of great conservatism. A type of stone utensil becomes established and remains with relatively little change through thousands of years. When, finally, a new type or method appears it does not, as a rule, suddenly replace the old. A period of transition follows during which the new becomes more and more prevalent until it is supreme. Even the appearance of an invading people does not result in a complete replacement of the utensils in use. The older forms remain for long periods and, in some cases, persist side by side with the products of more advanced methods, as was the case with the chipped arrow-head in the Age of Polished Stone. Stability is the rule, change the exception, until the pressure of population and contacts of people through warfare, trade, and intermarriage break down the conservatism of the groups and favor the acceptance of new ideas and inventions.

II. THE MODERN RACES

We have seen new races entering Europe at the end of the Paleolithic period. Apparently they are closely enough related to Crô-Magnon to be assigned to the same species—*Homo sapiens*—but are still sufficiently different from him and from each other to be classified as separate races. It should be clearly understood at the outset that we are not now dealing with language groups, nationalities, or castes. The term "race" is here used to designate a group of people having in common certain physical characteristics which distinguish them from all other groups, who now do or formerly did occupy the same or adjacent territory, and who have common descent.

No pure or unmixed races exist at the present time. Intermixture has taken place as the result of invasions, slavery, trade, and other causes, until in some regions there has been a thorough fusion through many generations. In such a group there are frequent reversions to type; individual variations also produce constant deviation so that we find great extremes within each race and subrace.

Many attempts have been made to define race in terms of stature, head or nasal form, color of hair, eyes, or skin, but all have proved unsatisfactory because of the great amount of overlapping between the groups. It is only by dealing with large numbers of individuals and by considering many criteria that we can strike an average which justifies the term "race."

By means of careful observations and measurements on both the living and the skeleton, enough significant tests have been developed to give us the main divisions of mankind and to allow us to unravel with considerable certainty the physical types involved in a mixed population. It is still a question where certain groups should be placed, and not all investigators are agreed as to terminology, but most anthropologists now group mankind in three primary stocks, within which are the divisions called races. These primary stocks with their main divisions are as follows:

I. Caucasoid

Races:

a) Nordic. Chiefly in northern Europe. Around Baltic and North Seas.
b) Alpine. Central Europe.
c) Mediterranean. In southern Europe and northern Africa. Around both shores of the Mediterranean.
d) Hindu. Northern and central India.

II. Mongoloid

a) Asiatic Mongoloids, including northern and central Chinese and many other subdivisions of northern Asia.
b) Malay. British Malaya, Dutch East Indies, Philippines, Formosa. Also includes considerable part of southern China, French Indo-China, and Burma.
c) American Indian.

III. Negroid

a) African Negro.
b) Oceanic Negro. Solomon Islands, New Guinea, and nearby islands.
c) Pygmy blacks of Africa, Andaman Islands, Malaysia, and perhaps of New Guinea.

This classification can be amply justified by the skeleton and by the body of living man, as we shall see in the following pages. It takes care of most of the living groups but still leaves in question the placing of the Australians, Polynesians, Ainus of Japan, and a number of small divisions such as the Veddas of Ceylon, the Sakai of the Malay Peninsula, and other minor groups of southeastern Asia.

Characteristics of race.—In order to see how this classification of mankind has been obtained we shall now review some of the more important characteristics to be observed on the skeleton and in living man. It will not be possible to consider the entire skeleton, so we shall restrict our study for the present to the cranium.

It is a matter of observation that at birth the skull is nearer its final size than any other portion of the skeleton, and that it attains the major portion of its growth at a much earlier period. Hence it is fair to assume that it will show more hereditary traits than portions of slower growth which may be subject to the effects of environment for a longer period.

The outer surface of the cranium, exclusive of the face, consists primarily of four bones—the frontal, two parietals and occipital (Fig. 116, *C*). The articulations of these bones are called sutures. The juncture between the frontal and parietal bones is called the coronal suture. Running back from this, in the median line, to the occipital bone is the sagittal suture; while that between the parietals and occipital bones is known as the lambdoidal. In embryonic life these sutures are lines of tough membrane, and at birth are still quite flexible, thus providing for the easy delivery of the child and also allowing for the rapid expansion of the brain.

The cranium may be considered, primarily, as an envelope or covering for the brain and it expands as the latter develops. Growth takes place along the sutures and it is a matter of observation that these become more and more serrated as the brain approaches its maximum development. In other words, the sutures on the cranium of a European child of three years are very sim-

ple; by the twelfth year they are relatively complex; while by the twentieth year they show great serration. There also appears to be direct correspondence between the complexity of a suture and

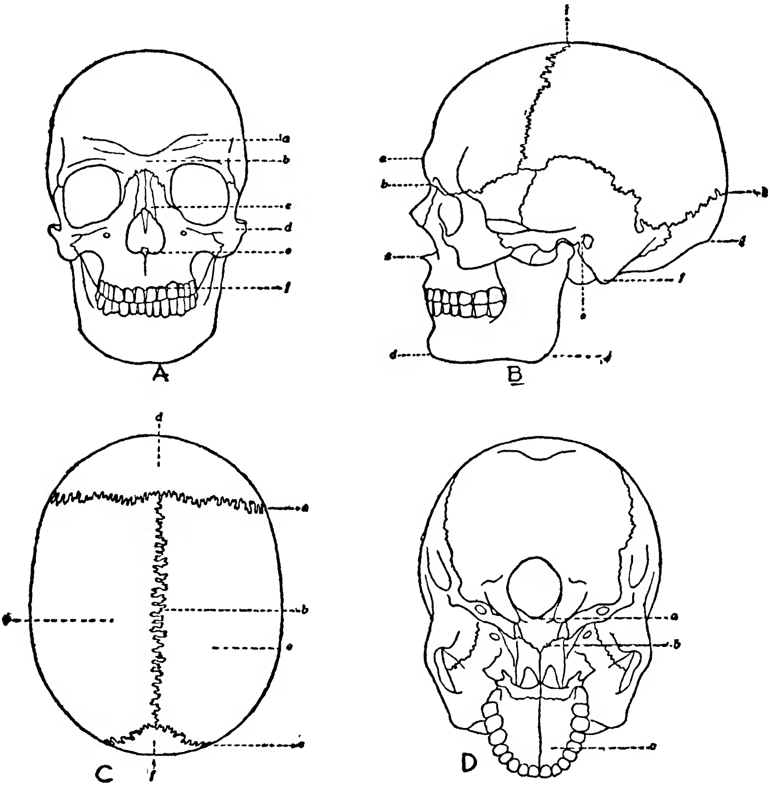


FIG. 116.—Human craniums, showing chief anthropometric features. *A:* (*a*) supra-orbital ridge; (*b*) glabella; (*c*) nasal bones; (*d*) zygomatic arches; (*e*) nasal margin; (*f*) alveolar point. *B:* (*a*) glabella; (*b*) nasion; (*c*) nasal spine; (*d*) gnathion; (*e*) pre-auricular point; (*f*) mastoid process; (*g*) inion; (*h*) lambdoidal suture; (*i*) coronal suture; (*j*) angle of jaw. *C:* (*a*) coronal suture; (*b*) sagittal suture; (*c*) lambdoidal suture; (*d*) frontal bone; (*e*) parietal bones; (*f*) occipital bone. *D:* (*a*) basion; (*b*) junction of basilar process with sphenoid; (*c*) hard palate.

the cranial development in that particular region, a fact which aids in the determination of race.

In general, the Negro skull shows greatest development in

the occipital region, and the lambdoidal suture is more complex than the sagittal or coronal. In the Mongoloids the greatest development is usually in the parietal regions and the sagittal suture is the most complex; while in the Caucasoids the frontal portion is the most pronounced and is accompanied by a very serrated coronal suture. It should be noted, however, that all the sutures of the Caucasoids are more complex than those of the Negroids, while those of the Mongoloids tend to be intermediate.

On the lower margin of the frontal bone, just above the orbits, an elevated crest, known as the supra-orbital ridge, is often seen. It is seldom present in females, but develops in males at about the fourteenth year. It is strongly marked in Caucasoids and Negroids, but is usually faint in the Mongoloids, except for certain American Indians. It is a valuable mark of age and sex and is of some value in racial classification, but it is not confined to the modern races nor is it a characteristic of man alone. It was a distinguishing mark of Neandertal man and today is highly developed in adult males of the chimpanzee and the gorilla.

Between the supra-orbital ridges, in the median line, is the most forward projecting point on the frontal bone, known as glabella. In the living it is usually on a line with the top of the eyebrows and directly above the nose. It is important as a measuring point on the skull and is also a mark of sex and race. It is slightly developed in females but attains prominence in the males of the Caucasoids, some American Indians, Australians, and Papuans, but is usually faint in African Negroes and Mongoloids.

Directly below the glabella, in the median line, is the point of articulation of the frontal with the two bones which form the skeleton for the bridge of the nose. This point of union is known as nasion. In all young children it is low, and remains so in most Negroids; is intermediate with the Mongoloids, but becomes high in the Caucasoids.

The nose must be considered under three headings: (1) the nasal bridge; (2) the nasal spine; (3) the nasal margins (see Fig. 116, *A*, *B*).

The bridge is made up of two bones which at birth articulate with each other in a very oblique angle, causing a low or flat nose like that found in the anthropoids. With age these bones develop until in the Caucasoids they tend to form a comparatively acute angle and give rise to a high nose. In the Mongoloids there is often a depression just below nasion, and the angle is less sharp; while in the Negroids it seldom develops far beyond the infantile stage.

The spine forms the support for the cartilage of the nose in the living and is a distinctive human characteristic. It is subject to considerable individual variation but nevertheless is a valuable criterion of race, for it is small, flattened, or absent in most Negroids; is small or rounded in the Mongoloids; but is long, broad, and sharp in the Caucasoids.

The lower margins of the nasal openings are also important. In the anthropoid apes there is no sharp line between the nasal openings and the incisor fossae; indeed a trough more frequently takes its place. Somewhat the same condition is to be found in the Negroids, but a sharp line or crest terminates the nasal openings in the Caucasoids; while in this characteristic the Mongoloids again occupy an intermediate place.

Directly below the nasal spine is a point on the alveolar margin, directly between the middle incisor teeth, known as the alveolar point or prosthion. On the living it closely corresponds to the center of the depression in the upper lip. It is primarily of value in measuring the forward projection of the face. If a line is drawn from the tip of the nasal spine to the alveolar point it will be found to be nearly perpendicular in the Caucasoids, somewhat slanting in the Mongoloids, but generally quite oblique in the Negroids. In other words there is in the upper jaw of the Negroids a distinct forward projection, a condition known as prognathism. This is to a large extent dependent on the shape of the hard palate and the alignment of the teeth. When the skull is examined from below, the hard palate is seen lying within the alveolar arcade. The curve of this arch varies with race and seems directly re-

lated to the change in size and points of eruption of the teeth which have taken place during man's evolution. In the Negro the arch assumes a U-shape, while in the whites the posterior arches diverge, making a parabola.

The subject of human dentition is much too complex to be discussed in this chapter. Only one very striking characteristic will be mentioned. In the Mongoloids the upper incisor teeth show a depression on the inner surface, and on each side of this is a ridge of enamel which produces the so-called shovel-shaped incisors.

The breadth of the zygomatic arches—cheek bones—is of some importance in describing race. They attained such great width in Crô-Magnon man that the face appeared to be out of proportion with the balance of the skull. Somewhat the same condition is found among the Eskimos and is often given as a distinguishing mark of the northern Mongoloids. However, a slightly different situation exists in the latter group: here we often find a distinct widening and forward projection of the malar bones (the anterior portion of the arch) which gives to the face the characteristic broad and flat appearance.

The mandible, or lower jaw, presents some points of racial value. The most forward point, in the median line, on the chin is known as gnathion, or the mental point. Possession of a prominent chin is a characteristic not shared by any of the animals closely related to man, and one in which the Caucasoids show the greatest development. It is rather weak in the blacks and was practically absent in Neandertal. It should be observed, however, that the possession of a chin is not a mark of advancement but seems to be in part due to a loss of or diminution in size of the teeth. The "weak chewers," in general, are those of greatest chin development.

The angle made by the ascending ramus of the jaw with the lower border is also significant. In the child it is very obtuse, but, with age and the eruption of the teeth, it becomes more and more acute, until in the whites it approximates a right angle; the blacks, however, tend to remain much closer to the infantile condition.

When the skull is viewed from the side, the outer opening of the ear (the external auditory meatus) is seen near to the center of the lower border. At the middle of the front margin is the preauricular point which corresponds to the tragus or fleshy prominence in the living. A short distance behind the opening of the ear is a nipple-shaped projection—the mastoid process—which develops more strongly in males after the age of puberty. It is usually large in Caucasoids and Oceanic Negroes, but is rather weakly developed in the African blacks.

At the back of the head, and a little below the meeting point of the sagittal and lambdoidal sutures, is a bony projection known as inion (Fig. 116 *B*, *g*). It rarely appears in females, and is slightly developed in the Mongoloids, but is prominent in mature males of both Negroids and Caucasoids.

Near the base of the skull is the foramen magnum, the opening through which the spinal cord passes. At the middle of the anterior margin of this foramen is an important measuring point called basion. Projecting forward from this is the basilar process which finally meets with the sphenoid bone (Fig. 116 *D*, *b*). The point of union remains a tough cartilage until about the eighteenth year, when it begins to ossify. By the twentieth year it becomes solid bone, but the point of union remains visible for two or three years longer, thus affording an excellent guide for determining age.

Age can also be ascertained with considerable accuracy by the eruption and wear of the teeth, by the ossification of the long bones and pelvis, and by other observations which cannot be discussed in this volume.

Cranial capacity is another important criterion. In a general way it corresponds to the volume of the brain, and this again seems to be roughly correlated with intelligence. It is the measurement which farthest separates man from the anthropoids and lower animals, and when used in a large number of cases, is also an index of race. It cannot be inferred, however, that a race or individual is inferior to another because of lesser capacity alone, for the volume of the brain is influenced by other factors such as

stature, age, and sex. Broad-headed groups usually exceed in cranial capacity the narrow-headed groups of like stature, and males usually exceed females, but there are many exceptions to this rule and great individual variation is to be found in every population.

We have considered some of the more important observations to be made on the cranium and have established measuring points. It is now possible to proceed still farther by a system of precise measurements.

The greatest length of the head is obtained by measuring from glabella to the most distant point on the back of the skull in the median line. The greatest breadth is taken wherever found—usually above and behind the ears. The height of the head on the living is taken from the pre-auricular point to the vertex—the highest point on the top of the head in the median line. On the skull the measurement is usually from basion to vertex.

With these measurements we can now determine the length-breadth, the length-height, and other indices.

The cephalic index is the ratio of the breadth of the head to its length when the latter is taken as 100. It can be expressed by the formula $l:b::100:x$. If the index is 80 or above the skull is known as brachycephalic, or short head; if it is between 75–79 it is called meso-cephalic, or medium head; while skulls with an index of less than 75 are dolichocephalic, or long head.

Used in large averages, the cephalic index is valuable for ethnic classification. All Negroids, except the pygmies, are dolichocephalic; all Caucasoids, except the Alpine race, are likewise dolichocephalic; while nearly all Mongoloids are brachycephalic or meso-cephalic.

The value of this index is greatly enhanced when we consider the height of the skull. The Negroid cranium tends to be long, narrow, and relatively low, while that of the dolichocephalic Caucasoids is high. Likewise the Alpine race and the Mongoloids are, in part, to be distinguished from the brachycephalic pygmies by the greater height of the head.

Next in importance is the nasal index. This is the ratio of the width to the length of the nose, using the same formula as for the cephalic index. On the skull the length is obtained by measuring the distance from nasion to the tip of the nasal spine. On the living it is taken from nasion to the point where the nasal septum meets the lip. The greatest width of the nasal opening on the cranium and the maximum across the nostrils of the living are measured. Skulls in which the index is less than 48 are called lepthorhine, or narrow nose. This classification includes most of the Caucasoids and the Eskimo. When the index is between 48 and 53 it is known as mesorhine, or middle nose. Here we find most Mongoloids. If the index exceeds 53 it is called platyrhine, or broad nose. Most Negroids are found in this grouping. The index is somewhat different on the living, but the terms indicating narrow, medium, and broad nose are retained.

Many other observations and measurements are made on skull and skeleton, but these will be sufficient for our present purposes.

For the metrical description of the living there has been devised a very complete set of instruments which record stature, length of arm, leg, and many other features. By using these measurements it is possible to show the standard deviation from the mean and thus indicate the amount of intermixture of types making up a given group. However, a detailed description of this method of approach is beyond the scope of this chapter.

Observations on the living.—We now turn to a few of the more obvious characteristics of race which may be observed on the living. Stature is often given as a criterion and, if used in sufficiently large averages, has some significance. Within the Caucasoid division, for example, the Nordics are, on the average, taller and of heavier frame than the Alpines, and they, in turn, exceed the Mediterraneans. Color of skin is likewise of value in racial classification. In general, the Caucasoids are of light color, the Nordics being blond; the Alpines, white; the Mediterraneans, tawny white or "light brown"; but the Hindus range from brown to very dark sepia. The Mongoloids are much more uniform in

color and may be described as varying from a light to medium brown, but with a distinct yellowish, or saffron, undertone. All the Negroids are classed as black although even here different degrees of color may be distinguished.

Color of hair and eyes correspond closely to that of skin, so that we find light hair and eyes prevalent among the Nordics, with darker shades becoming dominant as we go south. Very dark eyes and hair are characteristic of the Mongoloids and Negroids.

Texture of hair is of considerable ethnic value. When we study it in cross-section we find that if the two diameters are nearly equal we have the straight hair typical of the Mongoloids (Fig. 117 *a*); when it is oval we have the wavy hair found among most Caucasoids (*b*); but when it is much flattened (*c*) we obtain the woolly, frizzly, or tufted hair so common among the Negroids. The amount of body hair is also significant, for it is abundant on the Caucasoids but very scanty on the Negroids and Mongoloids.

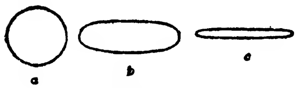


FIG. 117.—Shape of hair in cross-section.

In a considerable portion of the Mongoloids, especially in China, the eye opening appears to be somewhat oblique, and frequently a fold of skin arises 3–4 mm. above the inner side of the upper eyelid; from there to its attachment at the inner corner of the eye it partly overhangs the true lid. This is the so-called Mongolian fold. It is often present in white and negro children but usually disappears as the nose develops.

Shape and thickness of lips are also of descriptive value. In the Caucasoids the lips are thin and the upper rim tends to form a complex bow; in the Negroids they are thick and puffy and the bow is simple. Mongoloids fall between these extremes but in general are closer to the Caucasoids.

In all these characteristics we find even greater overlapping than we noted on the skeleton. But when we come to summarize all these traits we find that our earlier classification holds for the vast majority of mankind.

Recapitulation.—Let us now recapitulate the outstanding marks of race which we have observed.

I. Caucasoid

a) Nordic race: Tall; large of frame blond; light, wavy hair; blue, gray, or light brown eyes; long, narrow, and high head.

b) Alpine race: Shorter in stature; skin and hair darker than in *a;* light brown or hazel eyes common; short, broad, and high head.

c) Mediterranean race: Similar in head form to Nordic, but shorter in stature and lighter in frame; skin tawny white, often with an olive tinge; eyes very dark.

d) Hindu race: Corresponds closely to the Mediterranean except that the skin color is much darker.

General characteristics: Great development of the frontal region of the cranium; coronal suture most serrated, but all sutures complex; nasion high; nose long, narrow, and high; angle of the nasal bones acute; nasal spine large, broad, and sharp; nasal margins sharp; little or no prognathism; chin strongly developed; angle of the lower jaw approaches a right angle. In males there is a tendency toward strong development of the glabella, supra-orbital ridges, inion, and mastoid processes. In all races of this division the lips are relatively thin, and there is a considerable amount of body hair.

II. Mongoloid

In general the stature is below the average for Caucasoid. Skin color varies from light to medium brown with a yellowish or saffron undertone. Eyes are dark brown; Mongolian fold is common, especially among the Asiatic groups; hair straight and black; little body hair; head short, broad, and high, but mesocephalic, and even dolichocephalic groups are found in Malaysia and America; greatest development of the parietal bosses, above the ears; all sutures relatively complex but sagittal shows greatest serration (the Peruvians and some others are exceptions to this rule); zygomatic arches wide, malar bones often greatly developed giving the so-called "flat" face of the northern Mongoloids; nasion low; nasal bones intermediate in Chinese and Malay, but often high in American Indian; nasal spine small but sharp; nasal ridges rounded but not flattened; little prognathism; shovel-shape incisor teeth; chin, angle of jaw, and thickness of lips intermediate; slight development of supra-orbital ridges, glabella, and inion.

III. Negroid

Most African and Oceanic Negroes can be treated under one general heading, except that the latter are shorter in stature, and the nose is longer and higher.

Stature tall; light of frame; color of skin, chocolate brown or grayish black (some Hottentot-Bushmen groups have a distinct yellowish tinge); eyes dark brown or bluish black; hair black, curly, woolly or frizzly; little body hair; head long, narrow, and low; forehead retreating, but occipital region greatly developed; supra-orbital ridges and inion prominent in males; all sutures simple, but lambdoidal most complex; nasion low; angle of nasal bones very obtuse, often giving a concave bridge to the low, broad nose; nasal spine low and rounded, or almost lacking; nasal margins lacking or even forming troughs; prognathism marked; lips thick; chin weakly developed; angle of the jaw obtuse; mastoid processes small.

We have previously noted the fact that the Bushmen-Hottentot are lighter in color than the typical groups. They are likewise considerably shorter in stature, and in other ways show considerable variation; yet they fall distinctly inside the Negroid classification.

The Pygmy races of Africa and Malaysia are short in stature, and are brachycephalic, but otherwise conform to the foregoing description.

Several minor groups remain outside our classification. Chief among these are:

a) The Ainus of Japan. A people similar in many respects to the neighboring Mongoloids, except for having longer and narrower heads, and a great amount of wavy hair on head and body. They are described by Kroeber as a generalized Caucasian or divergent Mongoloid type.

b) Australoids (aboriginal inhabitants of Australia). This type shows many negroid characteristics, but has a great amount of body hair which is oval in cross-section. Other Caucasian features are often to be seen in individuals.

c) Veddas of Ceylon, Sakai of the Malay Peninsula, and other little known tribes of southeastern Asia. These groups are often placed together, but it is probable that they represent mixtures of invading groups with earlier inhabitants. Thus Veddas appear to have both Australoid and Caucasoid resemblances.

d) Polynesians. Much like the Malay, but apparently with an early Caucasoid admixture. Some groups also show negro blood.

All that has preceded has shown that racial differentiation is a fact and that it goes back to very remote times. Crô-Magnon and Grimaldi races give evidence that specialization toward the modern races had gone far at a period not less than 25,000 years ago.

Variation and specialization have proceeded until a comparison of the extremes gives us a picture of great diversity. In one division we find high stature, prominent nose, thin lips, straight

hair, and blondness of skin; while in another we find the pygmy with low, flat nose, thick lips, dark curly hair, and black skin. But as we study mankind in general we are impressed more by the similarities than by the divergences. This is particularly true if we compare the races of today with man of the Mousterian period. Neandertal man was human and in many respects corresponds to *Homo sapiens*, yet in other characteristics he resembles the anthropoids much more than do any of the living groups.

If we recall the whole history of the pre-human forms presented to us in the preceding chapters, we find it has been a record of specialization and development from a more generalized ancestral form toward modern man. Frequent attempts have been made to grade the modern races in an ascending scale according to their resemblance to the anthropoids. The retreating forehead, the low, broad nose, prognathism, and weak chin of the negro seem to place him nearer to the anthropoids than the other divisions; but on the other hand, in the amount and shape of his body hair, and the thickness of his lips he is farthest removed from the simians. All existing races show specialization; within each we find individual variations, and among all there is constant overlapping. No modern race is without evidence of its animal ancestry. Modern man still shows his close relationship to the anthropoids at every stage of his development, from the beginning of his embryological life to his adult form: many special features of the embryonic history of the two groups are peculiar to them alone, a clear indication of close kinship.

It is impossible to put man into a laboratory and study him through several generations, and so it is difficult to obtain authentic information as to the exact results of race mixture, of acceleration and retardation. But all the evidence at our command indicates that man is an animal, and that, like all other animals, he is subject to the effects of environment, to variations and mutations, and to the same laws of descent.

SELECTED REFERENCES

1. A. L. Kroeber, *Anthropology* (Harcourt, Brace & Co., 1923).

2. George G. MacCurdy, *Human Origins* (Appleton & Co., 1924).

3. Henry F. Osborn, *Men of the Old Stone Age* (Scribners, 1923).

4. R. A. S. MacAlister, *A Text Book of European Archaeology* (Cambridge University Press, 1922).

5. Boule, *Fossil Men* (London: Gurney & Jackson).

6. H. Obermeyer, *Fossil Man in Spain* (Yale University Press, 1925).

7. A. Hrdlička, *Most Ancient Skeletal Remains of Man* (Smithsonian Report, 1913).

8. Louis R. Sullivan, *Essentials of Anthropometry* (American Museum of Natural History).

CHAPTER XIII

THE FACTORS OF ORGANIC EVOLUTION

HORATIO HACKETT NEWMAN

Facts versus factors of evolution.—The reader should now be in an excellent position to form a judgment as to whether evolution is a fact or merely a hypothesis or a "guess." The writers of the last six chapters have presented a representative array of the facts upon which the theory of organic evolution rests. The methods used by biologists in their attempt to reconstruct the ancestral histories of present-day forms have been described and exemplified. In many cases a plain story of orderly change has been presented.

While the main highways of evolution are now well marked out, some of the bypaths are still obscure. All the facts so far presented may be organized and interpreted on an evolutionary assumption. Thousands of other facts have been satisfactorily explained on similar grounds, and there are at present no known facts contrary to the principle of evolution. For these reasons scientists the world over agree that the validity of the principle has been amply demonstrated. Many go so far as to rank evolution as a law of nature and assign to it a rank equal to that of the law of gravitation, the Copernican theory, the atomic theory, and other great scientific generalizations. The basis of its validity is the same as theirs, for they all severally owe their high place in human regard to the fact that they explain and rationalize and unify the facts of nature. This is the only kind of validity that is claimed for any law of nature. Let us then rest assured that the truth of evolution is demonstrated.

Not only is this so, but we can go further and say that the course of evolution of many groups may now be described with a very considerable degree of confidence. Many of the details of

the evolutionary history of plants, of the lower animals, of the higher animals, and even of man have been worked out. We know, therefore, not merely that evolution has occurred, but we also have much information about its general trends and, in some instances, can give a detailed history of successive changes leading from primitive ancestors up to specialized modern forms. About these matters there is essential unanimity among scientists, but there the unanimity ends, for when we come to the much more difficult and technical matter of the why and how of evolution we find almost as many shades of opinion as there are persons competent to form them.

While it may be generally agreed that certain causal factors co-operate to bring about evolution, few evolutionists would attach the same relative importance to the various factors. This is what is really meant when it is said that biologists are not at all in agreement about evolution. All are agreed as to the general fact and as to its main trends, but there is much disagreement of a technical sort as to the relative values of the co-operating causal factors.

The anti-evolutionist demands too much when he says: "Tell me exactly how a new species arises or what caused man to emerge from his primitive state. Unless you can explain exactly why and how evolution has occurred, you cannot expect me to believe in it." If one were to be consistent in following out the implications of this line of reasoning, he would be forced to deny the existence of many of the plainest facts of observation, for some of these are as little understood in terms of their mechanism or causes as is evolution.

Nothing could be plainer, for example, than the facts of individual development. One can follow the whole history in detail from the minute single cell (the egg) up to the complex adult. One can see the limbs, the eyes, the hair, the teeth develop from their primordia. Even the novice can see most of these facts and only the physically or mentally blind could deny that they are facts; but when one requires us to explain these facts on a causa-

mechanical basis he is making a very exacting demand. The truth about the matter is that very little is known of the causo-mechanics of individual development. Because we do not understand in terms of known laws how and why an embryo develops, shall we then deny the plain demonstrable facts of development? Yet, this, absurd as it may seem, is exactly what the anti-evolutionist does with the problem of racial development. Because we cannot here and now tell him exactly the mechanism of evolution, he refuses to believe in it and offers as a substitute an explanation contrary to all the known facts.

Sometimes we biologists go rather far in our admission of ignorance about the causo-mechanics of evolution. In our anxiety to make the point that the fact of evolution is in no way dependent upon our knowledge of its causes, we not infrequently belittle our present knowledge of the factors that underlie the orderly changes we call evolution. As a matter of fact, we know a great deal about the causal factors—far more than even the most sanguine biologist of a generation ago could have hoped to discover. This is an age of rapid discovery in the field of evolution; most of our knowledge regarding its mechanism has come within the present century.

The factors of evolution.—Four great basic factors are generally held to be responsible for organic evolution: (*a*) the change factor (variation), responsible for the introduction of new characters and for producing new combinations of old characters; (*b*) the persistence factor (heredity), responsible for the continuity, stability, and unity of all life; (*c*) the guiding factor (selection, and possibly orthogenesis and the Lamarckian factor), responsible for adaptation and whatever of orderliness actually exists in the evolutionary process; (*d*) the dividing factor (isolation in the broadest sense), responsible for the adaptive divergence of types and the splitting up of groups into taxonomic types such as species. For the sake of brevity let us speak of these four co-operative causal factors as variation, heredity, selection, and isolation.

With variation alone and no heredity, the living world would

be a chaos; there would be no genetic connection between the varying types of one generation and those of the next, no persistence of characters beyond a single generation. With heredity alone and no variation there would be merely persistence of one original form; the organic world would be at a standstill and all organisms would be alike. With both variation and heredity but no selection or other guiding principle the world would be peopled with monstrosities that under normal conditions do not survive, and there would be no orderliness in the evolutionary process. With variation, heredity, and selection but no isolation of groups there would be only one evolutionary series and only one type of fitness instead of the branching system of organisms and the multiplicity of adaptive types that actually exist.

While there is very little controversy as to the reality and importance of these four factors, there is little consensus of opinion as to the validity of orthogenesis concepts and the Lamarckian hypothesis. These, if real factors at all, may be classed as minor guiding factors. The Lamarckian hypothesis will be discussed in connection with the problem of fitness. The orthogenesis concept will be passed over without discussion, for the experts are unable to agree even as to its reality, much less as to its causes.

The four main factors of evolution are so intimately interdependent that it is almost impossible to present a separate account of each. It therefore seems best, now that we have classified and characterized them, to describe the operations of the factors as they work together in various genetic processes and to discuss various problems in which these factors are involved. Let us begin with a few comments upon the relation of heredity and environment.

A great biological problem.—The units of life as we know them are individuals, or organisms. Even within the limits of a species one encounters the utmost individual diversity. No two individuals are exactly alike; not even are two leaves on a tree or two scales on a fish exactly alike. Hence every individual is unique. Our first problem is that of determining just why each individual is

just as it is. Broadly speaking, the peculiarities of an individual result from the co-operation of two factors, an intrinsic factor, heredity, and an extrinsic factor, environment. Some writers would include training as a third factor. Logically, however, there is no middle ground between intrinsic and extrinsic. Therefore, it seems best to consider training as one aspect of the environment.

Heredity and environment.—The heredity of an organism includes everything that is passed along from one generation to another through the protoplasmic organization of the germ cells, both paternal and maternal. Typically, a new individual starts out in life as a single cell (zygote) produced by the union of two parent germ cells (gametes) known respectively as the egg and the sperm. The zygote is capable of developing only under certain definite environmental conditions. The environment not only conditions development but also determines to some extent the course and the character of development. Every peculiarity of an organism is the product of a long series of interactions not only between the organism and the environment but among different parts of the organism. A change in the environment may make a fish zygote develop into a somewhat different fish, but it cannot produce a new species of fish. Nor can similarity of environment cause the zygotes of two different species of fish to become alike. Environment then can modify development only within certain limits.

Exactly what is inherited? Obviously, developed structures are not inherited. The germ cell (zygote) has no eyes, no teeth, no brains, but it does contain specific protoplasmic materials capable under favorable environmental conditions of developing a particular kind of eyes, teeth, and brains. Change any one of the essential environmental conditions beyond a certain definite point and the resulting organism is modified. Usually it is necessary to change the environment somewhat radically in order to render the organism abnormal, for there is enough physiological elasticity in organisms to resist the disturbing influences of slight environmental changes. To obtain what we call a normal organ-

ism both a normal heredity and a normal environment are necessary, but fairly wide ranges of diversity in the environment are powerless to cause any measurable departures from normal development.

FACTS AND THEORIES OF HEREDITY

For a long time mankind has been aware of the general facts about heredity. This is attested by the numerous aphorisms, such as "Blood will tell"; "He is a chip off the old block"; "He comes from good (or bad) stock." An old slogan of stock breeders is "Breed the best with the best and you will always have the best."

The first attempt to systematize the available data about heredity was that of Charles Darwin. In his famous book, *Variation of Animals and Plants under Domestication*, he presented a large amount of data about heredity, but his attempt to interpret the facts was largely a failure, for two reasons. First, there was no definite understanding about germ cells and the processes of sexual reproduction; second, in all hybridization experiments the individual as a whole was considered as the unit of heredity. Darwin also made the mistake of assuming that all variations have a somatic origin and that changes in the body are registered in the germ cells by means of a purely hypothetical mechanism known as pangenesis, now completely discredited.

Weismann took a position utterly opposed to that of Darwin in that he considered that all heredity as well as all variation have their mechanism in the germ cells. He conceived of an unbroken line of germ plasm running from generation to generation. Under certain conditions, as when an egg and a sperm unite, the germ plasm froths up and develops a sort of excrescence, the somatoplasm. This is the body of the next generation and acts as the home and shelter of the immortal germ plasm. The body lives for a time and then dies, but the germ plasm goes on forever. This theory has for one of its corollaries the view that the germ plasm is independent of the body except for shelter and maintenance, and that changes in the body have no more effect upon the germ plasm than do the surface waves upon the depths of the sea.

Weismann's germ-plasm theory has had a wide acceptance in genetic circles. There is considerable dissent from the idea of the apartness of the germ plasm, but the essential features of the idea of the continuity of the germ plasm seem to be firmly established.

How are the characters of the individual represented in the germ plasm? This is perhaps the leading problem of genetics. Weismann thought that there was a specific determiner in the germ plasm for every character of the organism and that in the course of development the various determiners were segregated into different groups of body cells in such a way that each kind of cell got its own specific determiner. The germ cells, however, remain unchanged from generation to generation, each containing all the determiners characteristic of the species. This theory, while it contains more than a grain of truth, has been profoundly modified by subsequent discoveries.

The work of Gregor Mendel actually preceded that of Weismann by a good many years, but it was not appreciated until after the germ-plasm theory became current. Mendel, prelate in charge of a wealthy monastery at Brünn, in Austria, performed an extensive series of hybridization experiments with a number of varieties of cultivated peas. His analysis of results, a model of scientific method, was presented before an obscure local scientific society in 1865. Unfortunately it was virtually lost to the world for thirty-five years but was rediscovered in 1900. The rediscovery of Mendel's paper, *Researches on Plant-Hybrids*, was a great event, for it marked the beginning of scientific genetics. The early hybridizers before Mendel thought of the individual as the unit of heredity and considered that hybrid offspring were merely intermediate in type, that there was a sort of an averaging up of hereditary differences. Mendel came to the conclusion that the individual is not the unit of heredity, but that each individual is a complex of many independently heritable characters that may be separated from one another and recombined in the various offspring in a great variety of different ways. There is a regularity

and definiteness about the separation and recombination of character differences that has come to be expressed in the form of certain rules or laws that are now called Mendel's laws.

MENDEL'S LAWS

The law of dominance.—Almost all of the unit characters show two or more different forms or expressions. Thus there are brown eyes, blue eyes, and hazel eyes; straight, kinky, and wavy hair; tall, short, and medium stature; broad and narrow nose. As a rule, two different expressions or forms of the same character are mutually exclusive, any single individual showing one or the other. When two individuals, differing with reference to a single unit character, mate, their offspring will show one or the other character expression. Thus a pure black guinea-pig when mated with a pure white or albino individual will have none but black offspring.[1] That character difference which appears in the offspring to the exclusion of the other is known as dominant; the one that fails to appear, as recessive. Any two characters that show the relation of dominance and recessiveness and that segregate after the fashion shown in the next paragraph are known as allelomorphs.

The law of segregation.—This law is sometimes called the "Law of the Splitting of Hybrids," and is undoubtedly the most significant and far-reaching of all the laws of heredity. We may illustrate the workings of this law by a continuation of the experiment involving the mating of black and white guinea-pigs. The first generation black hybrids (now universally known by the shorthand expression, F_1) are interbred and, strangely enough, some of the offspring of the next generation (F_2) are black and some white, in the very definite ratio of three blacks to one white.[2] Thus the hybrids have split up in their offspring into the two

[1] In man the inheritance of skin color follows a more complex scheme than this and is explained in chap. xiv, pp. 426–27.

[2] The exact ratio is only attained when large numbers of offspring are produced. Any given litter of young is likely to fail to give exactly the statistical ratio.

forms that were originally bred together. The same thing happens in every case where only one pair of allelomorphs is concerned, whether we are dealing with plants, lower animals, higher animals, or man. It is a universal law that in the F_2 generation there will appear on the average three dominants to one recessive.

This ratio, however, does not quite reveal the whole story, for when we interbreed the F_2 individuals we get some further information. Thus, when the recessives of F_2 are interbred they give nothing but recessive offspring, but when we breed from the dominants we find that they are not all alike. One out of three blacks, when crossed with a white, will give all black offspring, showing that it is a double dominant; two out of three blacks, when crossed with white, give half black and half white offspring, thus revealing their hybrid composition, for the white individuals must have inherited their character from both parents. Our analysis shows that the ratio three black to one white is inadequate and should be modified to read one pure black to two black whites to one pure white, or in other words, one pure or double dominant to two dominant recessives to one pure or double recessive. A shorthand expression for this is the formula,

$$1\,DD : 2\,Dr : 1\,rr.$$

EXPLANATION OF MENDEL'S LAWS

In order to understand the mechanism responsible for this orderly behavior of hereditary characters and the observed ratios of dominants and recessives, it is necessary to state the chromosome theory of heredity. In a previous chapter (chap. vi) the finer structure of the life-unit, the cell, was described and especial emphasis was placed upon the chromatin and the definite organization of the latter into chromosomes. It was also shown how in cell division the chromosomes are split lengthwise so that half of each goes to each daughter cell.

Certain further facts about the chromosomes must now be revealed. First, the set of chromosomes in every cell of the body is not a single but a double one, for there are two of each kind of

chromosome. The reason for this is clear: the original fertilized egg cell (zygote) is a double cell produced by the union of a female germ cell (egg) and a male germ cell (spermatazoön). Each of these gametes contributes one complete set of chromosomes. Furthermore, every pair of chromosomes is qualitatively different from every other in that it carries a different set of chemical packets—genes, or character determiners. But the question has probably already arisen in your minds: How do the gametes come to have a single set of chromosomes, while the zygote and all other cells have the double set? The answer to this question is given in the following description of the process known as *meiosis*, a remarkable process that may well be considered as the chief mechanism of variation.

While the body of an individual is undergoing development the germ cells are relatively dormant, but there always comes a time (we may call it the period of sexual maturity) when something takes place in the germ cells that is never duplicated in body cells: they undergo a process of chromosome reduction resulting in the formation of gametes, each containing a single set of chromosomes.

Stripped of certain technicalities, this is what happens (Fig. 118). Just before the reduction process the homologous chromosomes come together and unite in pairs forming temporarily double chromosomes (synapsis). When the cell starts to divide by mitosis[1] the double chromosomes line up in the equator of the spindle, each pair so arranged that one component is pointed to each pole of the spindle. It is a matter of pure chance whether in any instance the maternal or paternal chromosome will be directed to a given pole. Then, instead of each chromosome splitting lengthwise and half of each going to each daughter cell, the double chromosomes merely part company (disjunction) and one whole chromosome of each pair goes to each daughter cell. Thus two cells are formed each with half the original number of chromosomes. Typically, another maturation division follows in which

[1] For a description of mitosis see pp. 183 ff. and in Fig. 118.

ordinary mitosis takes place, giving rise to four gametes from each original germ cell.[1] Parenthetically, it may be said that all male gametes (sperms) are functional, but only one of the four

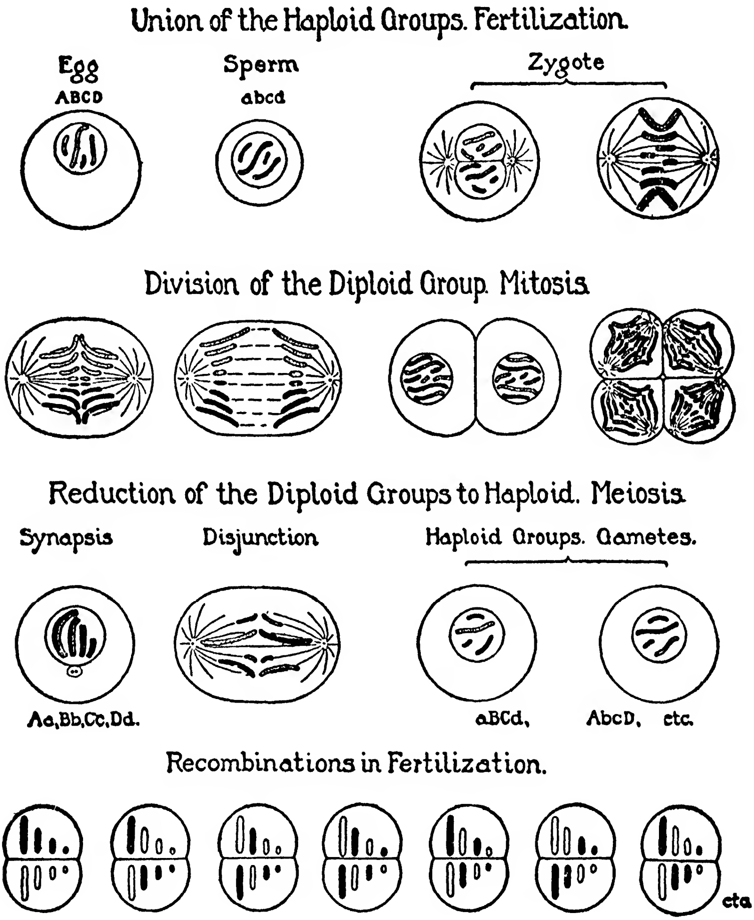


Fig. 118.—Diagrammatic survey of the chromosomal mechanism responsible for Mendelian ratios. In the bottom row only a few of many possible recombinations of maternal and paternal chromosomes are shown. (From Wilson.)

[1] Both maturation divisions may be partly reductional owing to crossing-over prior to disjunction. This is, however, too technical a matter for present discussion.

female gametes is functional, owing to the fact that the division of the cytosome in each maturation is extremely unequal, resulting in one large, yolk-laden egg and, typically, three tiny, abortive eggs (polocytes) without much substance except the chromosomes.

But, you may well ask, what has all this to do with Mendel's laws of heredity? It has everything to do with them, as we shall now show.

Assume that black fur and white fur in guinea-pigs have their genes in a particular pair of homologous chromosomes. The pure-bred black parent has two black-bearing chromosomes and the pure-bred white parent two white-bearing chromosomes. The reduced germ cells (gametes) of one parent will each have but one gene for black, those of the other parent but one gene for white. When the gametes unite (the process is known as fertilization), the zygote, or union cell, will have one gene for black and one gene for white; but black being dominant, no white individuals appear in F_1. That the white genes are not injured or affected in any way is well shown by the sequel. The F_1 hybrids (black) then form gametes as follows: the two homologous chromosomes (one carrying the black, the other the white gene) pair and in the reduction division go to different gametes, half of the gametes of each individual being "black" and half "white." When F_1 males and females are interbred a pure chance union of the two kinds of gametes from the two parents will take place. Once out of four times on the average a "black" will unite with a "black," once out of four times a "white" will unite with a "white," and twice out of four times a "black" will unite with a "white." Of course, you recognize in this result the familiar ratio of 1*DD* : 2*Dr* : 1*rr*. Hence it is obvious that the process of chromosome pairing, reduction, and recombination is exactly the kind of mechanism needed in order to account for Mendelian ratios.

The purity of the gametes.—The chromosomal behavior just described not only accounts for segregation, but for its corollary, the purity of the gametes, by which is meant that a gamete is always pure for one or the other alternative gene or allelomorph.

It cannot contain both, for a gamete has only one of each kind of gene. No more significant fact about heredity could well be given than this: it is absolutely fundamental.

HOW PARENTAL GENES ARE COMBINED IN AN ALMOST INFINITE NUMBER OF WAYS

Not only does the chromosomal mechanism involved in maturation and fertilization account for the regularity of Mendelian ratios when but one pair of allelomorphs is considered, but also adequately accounts for the almost infinite variety of combinations of parental characters seen in offspring. Let us begin with a simple case of assortment and recombination of but two pairs of allelomorphs. To black and white fur in guinea-pigs we may add smooth and rough coat. "Rough" is dominant over "smooth." Mate a black, smooth-haired guinea-pig with a white, rough-haired one (Fig. 117). The F_1 generation will be all "black rough," for F_1 individuals show only the dominant characters. Interbreed the F_1 hybrids and we get the following F_2 ratio: nine black rough to three black smooth to three white rough to one white smooth. In order to explain this ratio we need merely assume that black and white lie in one pair of chromosomes, rough and smooth in a different pair. Also we must assume that each pair behaves as though it were alone and uninfluenced by the other pair. The "black smooth" parent will give only black smooth gametes (*Bs*), the "white rough" parent will give only white rough gametes (*wR*). Gametes (eggs and sperms) unite to form zygotes which will all have the constitution ***BwRs***. When these F_1 individuals form gametes, the latter must be pure for each pair of allelomorphs and we get but four different kinds of gametes from each parent (four kinds of eggs and four kinds of sperms) as follows: *BR*, *Bs*, *wR*, *ws*. If these unite with each other on a pure chance basis we may represent the result by the checkerboard method, shown on page 395.

Wherever both *B* and *R* are present the individual will be "black rough" whether or not the recessive characters are also

present. It is a simple matter to count nine out of sixteen that are black rough, three that are black smooth, three that are white

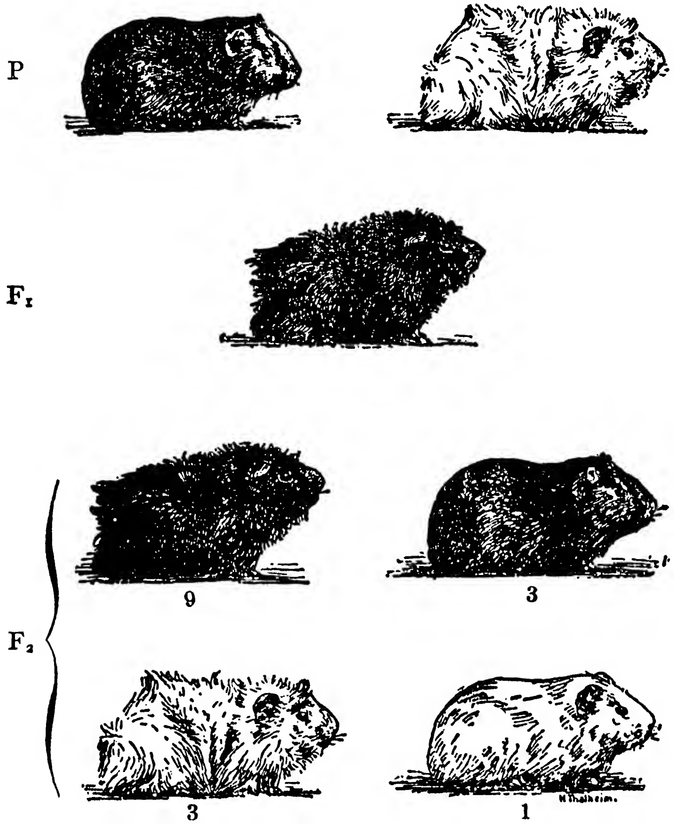


FIG. 119.—An example illustrating the simultaneous inheritance of two pairs of contrasted characters. The parents (P) are smooth black and rough white, respectively. The F_1 individuals are all black rough, showing only the dominant characters. The F_2 generation consists of 9 black rough, 3 black smooth, 3 white rough, 1 white smooth. (From Babcock and Clausen, after Baur.)

rough, and only one that contains no dominant genes and is therefore white smooth.

This amounts to a mere shuffling and dealing of alternative parental genes. When only two pairs of allelomorphs are con-

cerned we get four classes of offspring that look different and more than twice that many different types if we consider their breeding potentialities, for although four kinds of black rough individuals (*BRBR*, *wR BR*, *BR Bs*, *BR ws*) may look alike, they are different in their hereditary potentialities. If we add a third pair of allelomorphs, we double the number of different combinations, for we can combine either the dominant or the recessive with each of the types already seen. Each further pair of allelomorphs added doubles the former number of classes of gametes, and it will be readily seen that in such forms as man, who has as many as

Eggs \ Sperms	*BR*	*Bs*	*wR*	*ws*
BR	BR BR	BR Bs	BR wR	BR ws
Bs	BR Bs	Bs Bs	Bs wR	Bs ws
wR	BR wR	Bs wR	wR wR	wR ws
ws	BR ws	Bs ws	wR ws	ws ws

twenty-four pairs of chromosomes, the number of possible combinations in the offspring of one pair of parents will run up into the millions.[1] This is one of the reasons why no two individuals in a race are exactly alike.

Mendelian terminology.—In order that one may be able to discuss the results of experiments in heredity without constantly using awkward modes of expression, certain terms that have universal currency are here introduced. An individual (zygote) derived from two gametes alike in the genes under consideration is called homozygous. Thus in the diagram above, the four zygotes running diagonally across the square from upper left to lower

[1] Still wider ranges of new combinations are afforded by the crossing-over mechanism about which, for reasons that must be obvious to geneticists, nothing is said in this chapter.

right are homozygous for both pairs of allelomorphs. All other zygotes are derived from unlike gametes and are known as heterozygous. Some are heterozygous with respect to one factor (such as *BBRs* or *wwRs*) while others are doubly heterozygous (such as *BwRs*). All individuals that look alike, such as all black smooths, are said to belong to the same phenotype, while all that breed alike whether alike in appearance or not are said to belong to the same genotype.

FURTHER ANALYSIS OF THE MECHANISM OF HEREDITY

In Mendel's experiments with peas, the law of dominance held strictly true, but in subsequent experiments with both animals and plants the law of dominance proved more conspicuous for its breach than for its observance. Thus when two individuals with contrasting allelomorphs were crossed, the F_1 individuals exhibited a sort of blending of the parental characters.

The nature of blends.—Many cases came to light in which the F_1 hybrid, instead of showing the dominant character only, seemed to exhibit a blending of the dominant and recessive character. Thus a deep-red-flowered variety of plant (a Four-o'clock) crossed with a white-flowered variety gives pink-flowered offspring, that appear to be blends between red and white. The factor hypothesis, however, helps us to understand the situation without doing violence to the essential principles of Mendelian heredity. We assume that one parent has two genes or factors for red (*RR*) while the other parent has two genes that lack *R*, which we may represent as (*rr*). The gametes of the dominant parent will all have one gene for red and those of the recessive parent have no genes for red. Consequently, each F_1 zygote will have only one gene for red. In this case one gene for red makes pale red (pink) while two genes for red give deep red. In some of Mendel's experiments one gene for color in the F_1 generation was sufficient to give the full intensity of color possible under the conditions of life and two genes could do no more. Hence Mendel's double dominants and dominant recessives looked alike.

Blending may be thought of as imperfect dominance and represents a not uncommon situation. In all such cases, however, it is important to recognize that segregation due to purity of gametes holds good, for no real blending of genes has occurred. This is well brought out by interbreeding the F_1 pink-flowered plants just referred to. The ratio of F_2 offspring is one red to two pinks to one white, a typical Mendelian result and strictly in accord with the important F_2 formula, $1DD : 2Dr : 1rr$.

The factor hypothesis and the constitution of the germ plasm. —The unit character idea of Mendel implied that each character in the organism was dependent upon a single determiner in the germ cell. The modern idea is that each character may be due to the interaction of two or many independently inherited factors. Thus the color of a flower or that of a grain of corn may be due to two complementary factors neither of which alone produces color. Bateson crossed two white varieties of sweet peas and got a purple hybrid. Analysis showed that one white parent carried one necessary factor for purple, while the other parent carried the other.

Other kinds of factors are inhibitory, supplementary, cumulative. A great deal of light has been thrown upon the problem of the constitution of the germ plasm through the introduction of the factor idea. Unfortunately, however, to follow up the implications of this hypothesis would lead us into the intricacies of technical genetics. Without going into details, we may say that step by step geneticists have proceeded to push their scientific analysis deeper and deeper into the inner mechanism of variation and heredity until today they have succeeded in mapping out the details of the structure of the germinal materials of some of the species of animals intensively studied. It is now possible to state that the orderly arrangement of over four hundred genes has been worked out in one species of fly (*Drosophila melanogaster*) and that maps of gene locations have been published. Because of the almost incredible accuracy claimed for these determinations some skepticism as to their validity and significance still prevails in

biological circles. Yet the more one knows about the methods employed and the results obtained, the less grounds for skepticism are found. It is fair to say, then, that at least for some species the problem of the location of genes and the mechanism of their distribution in heredity is in its major aspects essentially solved.

THE NATURE OF GENES AND HOW THEY AFFECT CHARACTERS

The old view that each character of the adult is represented by a single particle in the germ plasm is now totally discredited. Hence it would be quite wrong to interpret chromosome maps as diagrams of determiners of unit characters. The orthodox modern view of the constitution of the germ plasm—a view based upon an immense mass of consistent data—is that it is composed of large numbers of discrete packets of different chemical substances, probably proteins; that these packets (genes or factors) are bound together in chains, each chain a separate chromosome; that there are probably several thousands of different kinds of packets; and that these have a definite, fixed, and orderly linear arrangement. The chief contribution of modern genetics has been to reveal this orderly disposition of heredity packets or genes. They are known to be at first disposed in a double set of linear chains, like loosely-strung chains of variegated beads. Like beads, the packets cannot change place unless the string be broken. The strings of packets are paired and for each packet in one of the paired strings there is a corresponding packet in the other. Some times the corresponding packets in two strings (homologous chromosomes) are chemically the same, but as often as not there may be minor differences between corresponding packets. We have already seen how the packets are shuffled and redistributed according to certain definite laws of heredity (Mendelian and Neo-Mendelian laws). If a given parent has two corresponding packets that differ chemically, he can give to each offspring only one or the other of these differing packets (see segregation and purity of gametes). Then come in the laws of recombination of packets when the gametes of two parents unite in fertilization.

Genes, then, are conceived of as discrete packets of chemical molecules each having a definite spatial arrangement with reference to the others, and each co-operating with many, if not all, other genes in producing the special characteristics of the organism. Even such a simple character as the red eye color of Drosophila has been shown to be due to the interaction of at least fifty genes, and probably hundreds of genes are concerned in producing the normal wings of this species of fly. If any one of the co-operating genes is altered or lost the character is changed. Thus a great variety of eye colors other than the typical red arise as the result of alterations in the various genes. In the case of the eye, a single gene alteration may rob the eye of all color, giving white eye, or it may only change the typical shade of red to another slightly different. The degree of change produced seems to vary according to the importance of the particular gene that constitutes a link in the complex series of chemical steps involved in the production of eye color.

From this point of view, the germ plasm (chromatin) of the organism is an extremely complex chemical laboratory with thousands of different reagents arranged in discrete packets and in definite order. This seems to promote a particular specific series of interactions whose end result is an organism with characteristics as specific as was the original complex laboratory of chemical materials.

We have already seen that almost infinite variety is imparted to the individuals of a species by the mere processes of sorting out and recombining the chemical packets. But this sorting and recombining gives rise to nothing actually new.

THE ORIGIN OF NEW HEREDITARY CHARACTERS

Differences in developed characters have been shown to be due to differences in the chemical packets or genes and to differences in the environment. Only by breeding successive generations under a constant environment is it possible to note changes in the genes. In the fruit fly, *Drosophila melanogaster*, Morgan

and his collaborators have observed about four hundred different gene changes in the last two decades. These so-called gene mutations affect changes in practically all parts of the body, the most obvious being those concerned with the color, shape, size, and texture of the eyes; size, shape, and texture of the wings; number, shape, and distribution of bristles; changes in legs, body regions, internal organs; and numerous physiological characteristics such as general health or viability. Many changes are so serious in character as to shorten life or prevent the completion of development.

Similar mutations of the gene type have been observed in many other animals and in not a few plants. In general, it may be said that any hereditary change that follows the laws of Mendelian heredity is due to a gene mutation. Doubtless in man many of the peculiar types of hereditary differences that are known to follow the laws of Mendel have arisen as gene mutations, though we lack exact information about these matters.

Chromosomal aberrations.—Another kind of germinal change frequently classed under the head of mutations is one that does not involve any qualitative change in the chemical packets, or genes, but is caused by additions of whole chromosomes. Thus in *Oenothera lamarckiana* (Lamarck's Evening Primrose), the classic example of a mutating plant, DeVries discovered a species that was producing many new types differing markedly from the parent species. Some of these new types proved to have an additional chromosome. This would mean that any particular mutant would have three of some one kind of chromosome instead of the usual two. The characteristics of any mutant seemed to be dependent upon which one of the seven different kinds of chromosomes appeared in triplicate. Another situation came to light when it was found that one of the mutants discovered by DeVries had twice the normal number of chromosomes, that is there were four of each kind of chromosome. There are various other possible permutations of these types of chromosomal aberration, most of which have been realized in Oenothera, in Datura, or in other species of plants and animals.

determined, and their 50 : 50 ratio is accounted for. In man the same mechanism is present as in Drosophila. Furthermore, al-

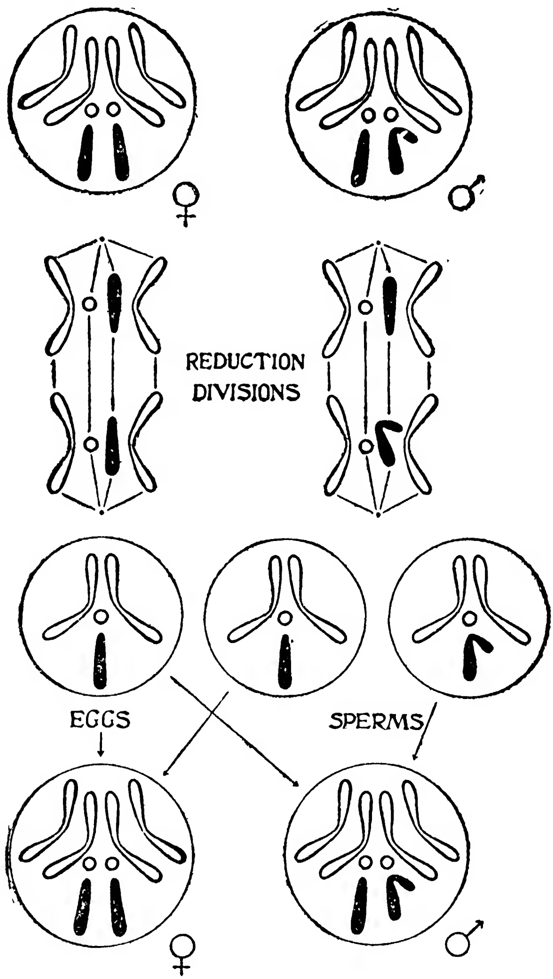


FIG. 120.—Diagram showing the mode of chromosomal behavior responsible for sex determination in Drosophila. The left-hand column shows reduction and recombination in the eggs, the right-hand column, that of the sperms. Arrows showing combinations (fertilization) of gametes to form zygotes. (From Babcock and Clausen.)

though there are many complexities involved in different groups of animals and plants, it may be stated that the principle holds good in every case where the facts are known. It will be seen that sex is truly inherited in that it follows a given distribution of the chromosomes. It may also be shown to be inherited according to definite Mendelian ratios.

Sex differentiation.—Whether an individual with a male or a female chromosome complex is irrevocably destined to become in its developed form a male or a female, respectively, is another question. It is known that, in some animals at least, the chromosome mechanism has to be reinforced by a hormone mechanism connected with the glandular elements of the gonads (ovaries or testes). In the absence of these glands the individual does not develop fully or else develops the characters of the opposite sex. When glands are exchanged between males and females some of the characters of the opposite sex appear. Moreover, it has been demonstrated that in some species of animals the sex that is chromosomally determined at fertilization may be reversed by environmental factors whose influence apparently overpowers that of the chromosomes.

The field of sex differentiation is a relatively new one and one about which information is accumulating at a rapid rate. However interesting it might be to describe some of the situations that have recently come to light in our own laboratory, we must refrain and proceed to our next main subject, the origin of adaptations.

CAUSES OF ADAPTATIONS

One of the outstanding facts in nature is the mutual fitness of the organism and its environment. So much impressed have men been with this fact, that they have commonly explained it as the result of intelligent design. The argument is, according to Paley, somewhat as follows: A watch is ideally adapted to keep time. Every part has a definite and a necessary function and all are co-ordinated into a unit. An organism is in many respects like a watch and it is natural to explain the adaptiveness of both watch

and organism in the same way. Since the watch is obviously the result of intelligent design, the organism is accounted for as a product of a purposed plan.

Now if all nature were adaptive and every part of an organism were as fit as the parts of a watch, the argument from design might hold. But examples of non-adaptive or even detrimental structures and functions are extremely numerous. Man is no worse off in this respect than any other organism, yet man has many poorly adapted or non-adaptive structures.

Think of man's vermiform appendix that is not only useless but often a source of grave danger and death; think of his useless ear muscles that are all present but can accomplish no useful function; think of the functionless breasts of males; think of the vestigial tail, the ill-adapted wisdom teeth, and many other obviously non-adaptive human structures. Does it seem reasonable to suppose that these useless structures were designed in their present form? If some parts of an organism are obviously not designed, is it likely that others were designed and that the useless parts merely slipped in by mistake? Such considerations as these, and others equally conclusive, make it impossible for us, as seekers after the truth, to accept the view that adaptation in nature is the result of intelligent design.

The over-enthusiastic followers of Charles Darwin are responsible for a greatly exaggerated emphasis upon the adaptiveness of organisms. They went so far as to assume that, because a group of animals or plants is alive and apparently prosperous, every part of the body and all of its responses to stimuli must be adaptive. When critical examination of many species was undertaken, the fact emerged that nature is full of examples of unfitness. Instances of non-adaptive characters mounted up to such an imposing total that some extremists have openly stated that the concept of adaptation in nature is a myth, that man has merely read into nature most of its adaptiveness. The opponents of the idea of adaptation call our attention to the utterly planless course of embryonic development. Instead of proceeding steadily forward as a planned

project should, the whole process is one of building up, tearing down, discarding, and remodeling. We are reminded that many insects carry useless and burdensome encumbrances, that many colors are present in organisms that never see the light, that there are many harmful instincts such as that of the moth for the flame. The natural conclusion from this line of argument would be that real adaptiveness is relatively rare in nature, and what little there is, is largely accidental. Such a view leaves little for the evolutionist to explain.

A sounder view is one that attempts to take a well-balanced middle ground between the worship of and complete skepticism about adaptation. Even though every organism possesses some unfit characters it seems certain that in every normal organism there must be some credit margin of fitness, else it could not survive. When we realize that the organic world is only relatively fit and that there exists much room for improvement, we are more likely to be open-minded as to the necessity of a naturalistic explanation of whatever adaptive characters organisms actually possess.

Categories of adaptation.—Biologists recognize that there are two main categories of adaptations: (*a*) those that are acquired by the individual during its lifetime by response of some sort to the environment or by functioning in an appropriate way; and (*b*) those that appear in the organism as though in anticipation of the rôle they are to play and not in response to any immediate need. Obviously, the two kinds of adaptive characters are very different and require different explanations. We may for the sake of brevity call the first kind of adaptations individual or acquired, and the second racial or hereditary.

EXPLANATION OF INDIVIDUAL OR ACQUIRED ADAPTATIONS

It has already been pointed out that there is a very profound mutual interrelationship between the organism and the environment. The organism fits the physical and chemical features of the environment; in fact, it is made up of materials taken from this

environment. There is a most intimate interplay between the materials within the organism and those outside of it. The result of this interplay is a definite structural and functional unit that we call an individual. It seems inevitable that the product of the interaction of two agencies shall partake of elements from both and shall, therefore, be intimately related to both. The appropriateness of the organism to the environment of which it partakes so intimately is what we call general fitness or adaptation.

It is a commonplace fact to experimental embryologists that almost any change in the effective environment of a developing organism results in a change of form or of function. Thus, while a vertebrate egg, such as that of a fish, under the prevailing, or normal, conditions, will develop a normal individual with one head and two eyes, it is easily possible by certain simple changes, such as lowering the temperature or decreasing the oxygen content of the water, to produce individuals with a narrowed head and a single cyclopian eye on top of it, or by other equally simple environmental changes to produce individuals with two complete heads on a single body or a single body with two tails. Since all of these anomalous types constitute typical responses on the part of the organism to a particular environmental condition they may be said to be molded by the environment that induces them. In exactly the same way the so-called normal condition is the result of a response of a particular kind of protoplasm to the particular environment that happens to prevail and is, therefore, called the normal environment. A large part of the existing fitness of the organism to the environment is, therefore, due to the fact that the environment controls development and molds the developing individual into a fit form.

Again, it is well known that many organs, such as the heart, for example, depend for their efficiency upon doing an appropriate kind and amount of work during the entire course of development. By interfering with the blood supply or with the nervous control of the developing heart one can readily cause it to stop beating and ultimately to atrophy. The heart, like many other organs,

becomes functionally efficient through practice. Hence much of its adaptiveness is the result of its own efforts and each heart has to acquire its own adaptive efficiency. This is probably true of all muscular activities and doubtless applies to nervous and glandular functions as well. Hence much of fitness is due to practice.

Still another type of individual adaptiveness is due to habitat selection. When we find various types of birds or fishes always aggregated in one out of a number of possible environmental complexes, and this particular complex seems to be the one best adapted to the particular species, we must not jump to the conclusion that the environment has influenced the species in a direct way. As Shelford has pointed out, it is easy to show that the particular environment is generally selected by a given species through a process of trial and error, individuals avoiding the less favorable environment and finally coming to rest in that spot where the adverse stimuli are least and where the organism is most nearly in equilibrium with its surroundings.

We see, then, that the general fitness and much of the special fitness of organisms may be the result of the direct interaction between the organism and the environment and must necessarily be reacquired by each individual. Such fitness is not so much a racial matter as it is an individual one and, therefore, lies within the fields of the physiology of development and of ecology rather than within that of the causo-mechanics of evolution.

THEORIES TO ACCOUNT FOR INHERITED OR RACIAL ADAPTATIONS

There are many adaptive characters that cannot be thought of as individually acquired through the molding effect of the environment nor through functional modification. Such characters reach their full adaptive value, or nearly so, without functioning in any way that would account for their special fitness. Thus the human eye is practically a finished optical instrument in the newborn infant, yet it can never have been used as such during the period of development. Similarly, the human lungs are finished and ready for use before the first gasping cry of the newborn

child fills the lungs for the first time with air. The well-developed breeding and nesting instincts of birds and other animals seem to appear without training or imitation. The color markings of many animals, their elaborate instincts, and many of their group relations, seem to be strictly inherited and little modified by the environment. It is the problem of explaining how such hereditary or racial adaptations came into existence that especially concerns evolutionists. Some sort of guiding factor seems to be responsible for directing evolution along the paths of fitness and definiteness.

Two entirely different explanations of the origin of hereditary adaptations have been offered, one by Lamarck and one by Charles Darwin. These may well be considered in the order given.

Lamarck's theory.—It is well known that any active organ or part of an individual tends to increase in size and in efficiency with use and to decrease in size and in efficiency with disuse. Similarly, organs change in direct response to alterations in the environment. No one denies these facts about the individual organism, but the crux of Lamarck's theory is that he believed that the effects produced in the body by use or disuse or by response to changed environment are inherited. This theory of Lamarck is commonly called the theory of the "Inheritance of Acquired Characters." In a word, it implies that the first category of adaptations (individual or acquired) may be transformed into the second category (racial or hereditary). In terms of the germ-plasm theory, it means that somatic changes are able to register themselves upon the germ plasm in such a specific way that the latter is capable of giving rise to the acquired character in the soma of the next generation without any effort on the part of that soma. A specific illustration will serve to sharpen the issue. We know that a musician may acquire a high degree of technical skill by assiduous practice. The question is, whether or not he will be able to transmit to his children any part of his acquired skill; whether a child of his born after he has acquired his skill is likely to be any better off with respect to musical skill than a child born before such training.

It seems unreasonable to suppose that a character that is a product of training in a parent should appear in offspring without training or with less training; yet this is a prevalent belief among non-scientific persons and of at least a few who are versed in science. If adaptive improvements resulting from training or reaction to environment were hereditary, it would be easy to account for almost any degree of adaptive perfection without recourse to other evolutionary factors. Unfortunately, however, there is little, if any, satisfactory experimental evidence that lends support to the Lamarckian theory. Consequently, while many biologists would like to believe in this theory, very few are able to convince themselves that it has any validity. Large numbers of experiments have been performed with the idea of proving that acquired characters are inherited, but without exception they have either given negative results or else are capable of being explained on other than Lamarckian grounds. Just at present there seems to be a newborn hope that the theory may return to favor. The reason for this is that several recent pieces of experimental work, while not actually demonstrating the inheritance of acquired characters, seem to favor its possibility. Reluctant as many of us are to abandon hope in the efficacy of the Lamarckian factor, candor forces us to admit that at the present time this factor has so little in its favor as to be of no value in our attempt to explain the cause of inherited adaptations. It should be said, however, that none of the experiments designed to test the inheritance of acquired characters has extended over more than a few years. This gives rise to a hope on the part of Lamarckians that if much longer periods of time were involved effects not noticeable in short periods might occur. This possibility must, of course, always be kept in mind, but it would be unwise to be very optimistic about it.

Darwin's theory (natural selection).—The theory of natural selection (survival of the fittest), while proposed as a mechanism for giving rise to new species, is now believed to be chiefly valid as a general cause of adaptations. The theory is the result of the

logical putting together of certain self-evident postulates and deducing from these certain apparently inevitable conclusions.

The postulates are as follows: (*a*) the geometrical ratio of increase: every species of organism, even the slowest breeding ones such as the elephant, produces enough offspring on the average to at least double the number of individuals each generation; (*b*) every individual differs from every other in all sorts of particulars, for there are no two exactly alike; (*c*) all individual differences of survivors are transmissible by heredity.

Taking these statements as self-evident, Darwin proceeded to build up his theory as follows: If all the offspring were to survive there would in a relatively few generations be neither food nor room for them all. There must, therefore, be competition for existence and the elimination of many. Since they all differ in many characters, some must necessarily be better equipped for the struggle than others, and, on the average, the best adapted, or the fittest, will survive. The survivors of one generation will be the parents of the next and will pass on to their offspring that complex of characters the possession of which has given them an advantage. In successive generations, because of the elimination of the least fit in each generation, the standard of survival would be raised and the survivors would progressively be more and more perfectly adapted to meet the struggle for existence. Under easy conditions adaptive advance would be slow, but under the spur of hardship the struggle would be keener and the criteria of survival more exacting. Thus hardship would act as a motive force in evolution.

Darwin conceived of life as a keen struggle for survival and was inclined to lay emphasis upon even the smallest differences, as is well brought out by the following quotation:

> It may metaphorically be said that selection is daily and hourly scrutinizing throughout the world, the slightest variations, rejecting those which are bad, preserving and adding up all that are good; silently and insensibly working whenever and wherever opportunity offers at the improvement of each organic being in relation to its organic and inorganic conditions of life. We see nothing of these slow changes in progress, until the hand of time has

marked the lapse of ages, and then, so imperfect is our view into long past geological ages, that we see only that forms of life are now different from what they formerly were.

If the postulates of natural selection are valid, there would seem to be no escape from the conclusions drawn, but there is at least one weak link in the otherwise logical chain. We now know what Darwin had no means of knowing, that the majority of small quantitative differences among the individuals of a species are merely somatic adjustments, and that, unless Lamarck's factor be in operation, these character differences could not be transmitted to the offspring of survivors. This objection, however, is not fatal to the theory, for we can rehabilitate it by substituting mutations for the minute individual somatic differences upon which Darwin depended. Mutations are now known to furnish the material for selection. We have seen that the majority of mutations are changes for the worse, but, unless they are seriously detrimental, they are likely to persist and be passed on to some of the offspring. At long intervals a mutation of a superior sort occurs and is at once incorporated as a racial asset. T. H. Morgan says:

> Such a view gives us a somewhat different picture of the process of evolution from the old idea of a ferocious struggle between individuals of a species with the survival of the fittest and the annihilation of the less fit. Evolution assumes a more peaceful aspect. New and advantageous characters survive by incorporating themselves into the race, improving it and opening to it new opportunities. In other words, the emphasis may be placed less on the competition between individuals of a species (because the destruction of the less fit does not *in itself* lead to anything that is new) than on the appearance of new characters and modifications of old characters, that become incorporated in the species, for on those depends the evolution of the race.

On the other hand, it must not be forgotten that characters, as such, do not survive or perish, but only whole organisms. A new character appearing in an organism may, however, in itself be a decisive factor in survival of the type. Thus most mutations are so harmful in their effect upon the individual possessing them that the latter under natural conditions would be unable to survive.

Hence, elimination or survival may result from one gene change. Thus, while single characters do not as such survive or perish, a change in a single character may settle the fate of the whole organism.

All organisms are mixtures of advantageous, neutral, and disadvantageous characters. An individual or a species that has a significant majority of advantageous characters might survive under certain relatively easy conditions. In this way it is easy to see why many successful species are burdened with useless or actually detrimental characters, for an organism with a large net credit balance of favorable characters can afford to carry as excess baggage a considerable load of liabilities in the form of neutral or mildly harmful characters.

Evolution, under either of these views, amounts to an accumulation, through the survival of individuals, of new characters. All mutations that occur, except the seriously harmful ones, survive in organisms that possess a considerable credit balance of adaptiveness. Racial change, then, is not so much a result of personal struggle as of a slow production and accumulation of hereditary changes capable of survival. This is the somewhat attenuated form to which Darwin's theory has been reduced.

It is now generally recognized that natural selection, while it may be said more or less satisfactorily to explain adaptations, fails tc throw much light upon the origin of species. Other factors must be called in to aid natural selection in this task.

DIVERGENT EVOLUTION AND THE ORIGIN OF SPECIES

As has already been said, variation, heredity, and selection alone could account for no more than one line of evolutionary change or one type of fitness. In order to account for the almost limitless diversity of adaptive forms and the intricate branching system of organic relationships it seems necessary to bring to the aid of these factors a dividing, or segregating factor. Broadly speaking, any factor that segregates individuals or groups of individuals belonging to the same species tends to favor divergence

of type. Geographic isolation, change in breeding season, the loss of interfertility between varieties, or even a change in habits; any of these, and no doubt other agencies as well, may act as dividing agents and serve to induce divergence of type and the consequent multiplication of species.

Darwin expressed the opinion that the tendency toward divergence is the result of the fact that competition is keenest among individuals that are most alike and whose life-needs are identical. Such forms tend to crowd into the same habitats and to compete for the same kinds of food. Any variations that would enable an individual or a small group to subsist upon somewhat different food or to live in a somewhat different environment would be of great advantage in that they would enable those individuals possessing them to occupy a relatively open field. Thus it may be said that diversity in itself has a high adaptive value, for it promotes the abundance of life upon earth, abundance being the ultimate objective of the life urge.

We have before us a picture of an extraordinarily diversified world occupied by innumerable kinds of specialized forms whose success has depended upon the exploitation of every nook and cranny of the earth's surface where life can possibly exist. With the pressure of life as an urge, the deserts, the abysses of the sea, the arctic ice, the darkest caves, and the inmost tissues of organisms are peopled with specialized forms adapted for all of these relatively unfavorable habitats. From this one can readily see the advantage of diversity and how it tends to favor divergence of type or the splitting up of relatively homogeneous groups into several new types.

Geographic isolation.—It will doubtless occur to the reader that in order to save an incipient new type from swamping out, it will be necessary in some way to prevent breeding between old and new types, or at least to put a premium upon breeding among individuals having the new character. Any sort of agency that will favor this sort of selective mating will aid in the establishment of a new species. The simplest kind of isolation is geographic. If

for example, a single fertilized female insect be carried off by wind or other agency to an isolated island, or across an arm of the sea, or over a mountain range, the peculiar hereditary characters that happen to be present in this one individual will then be set apart from the much wider range of characters found in the species as a whole. The necessary inbreeding of the offspring of such an individual will bring out many recessive characters. Some of these, such as winglessness in insects on oceanic islands or blindness in cave animals, might conceivably have considerable adaptive value under the changed conditions. Moreover, the mutations of the isolated group would probably be different from that of the parent group and, because of a different environment, there should be a different standard of survival for the two groups. The longer the separation, the greater would be the divergence between the old and the new, until the two groups would be sufficiently different to be adjudged distinct species or even distinct genera or families. The degree of divergence seems to hold a definite relation to the duration of the isolation.

In addition to geographic isolation, we find that purely biological factors may be equally effective. Let us assume, for example, that a new type arises through mutation whose chief effect at first is an accelerated or retarded development, involving a breeding season distinctly earlier or later than that of the old species. If the members of the new type have an earlier breeding season they would all be mated before the breeding season of the old group arrived. A later breeding season would be equally effective in preventing crossing between the mutant and the parent species. Lack of space forbids a discussion of other types of isolation. It seems obvious, however, that isolation is an important factor in evolution, favoring the divergence of type and thus the origin of new species.

Concluding remarks.—We have in the present chapter dealt with the principal known agencies that co-operate to give the result known as organic evolution. We know much about the mechanism and the laws of heredity, but little about the mechanism

of mutation. Our judgment is that natural selection is the most important directive factor, that isolation in a broad sense is an almost indispensable factor in the origin of new species. If there be other causal factors of evolution, we do not know enough about them as yet to warrant their discussion in this place.

In conclusion, it should be emphasized that the scientific study of evolution is still in its infancy. If as much progress shall be made in the next quarter of a century as has been made during the last we shall then be well on our way to an adequate understanding of the causo-mechanics of organic evolution.

SELECTED REFERENCES

1. W. E. Castle, *Genetics and Eugenics* (3d ed., Harvard University Press, 1924).

2. E. G. Conklin, *Heredity and Environment* (3d ed., Princeton University Press, 1919).

3. H. S. Jennings, *Prometheus (or Biology and the Advancement of Man)* (E. P. Dutton and Co., 1925).

4. H. H. Newman, *Evolution, Genetics, and Eugenics* (2d ed., University of Chicago Press, 1925).

CHAPTER XIV

HUMAN INHERITANCE

ELLIOT R. DOWNING

INTRODUCTION

The past two centuries have been marked by man's rapidly increasing control of the physical world. He has harnessed mighty steam and deft electricity, and by their aid has multiplied wealth and consequently physical comforts; he has cut continents in two and pierced mountain barriers, he has explored the mysterious frontiers of the universe and forced the invisible atom to reveal its structure. His control of his biological environment is progressing with amazing rapidity. He is restricting disease, reshaping plants and animals to suit his needs, increasing the productivity of species that cater to his wants and eliminating those that antagonize his interests. Man has made least progress in the control of his social environment. Just now he is intensely conscious of the need of such control and ambitious to accomplish it. Note that man's control of the forces about him is a control only in the sense that he aligns himself with such forces; he places himself or his devices in position to take advantage of these forces in the accomplishment of his purpose.

Heredity and environment in human life.—Science can contribute to this latest attempt at social control at least a clear-cut notion of the limitations of the field of "euthenics," which is the science that deals with the problems of the improvement of the social environment, as contrasted with the field of "eugenics." which is the science that deals with the problems of the improvement of the human stock. Apparently our potentialities are determined by inheritance; the opportunity they will have to develop, by the physical and social environment. Man's prolonged period of infancy and youth, together with the fact that he inten-

tionally brings environmental influences to bear on the growing young in their training, makes the environment factor particularly potent in his development.

The potency of inheritance in human life is well shown by Galton's studies of identical twins, twins that are of the same sex and look so nearly alike that they are often mistaken for each other by even their close friends or relatives.[1] The identity has been so close in certain instances that young children could not tell their own father from his twin brother; teachers spanked both for fear the guilty one would escape punishment or refrained from chastising either, lest the innocent should suffer. Such twins arise from the same fertilized egg. Galton found in the eighty-three pairs of identical twins studied that even when they were separated in early life and lived in quite unlike environments, they remained very similar, not only in physical characters but in mental traits. Thorndike's studies[2] of 50 pairs of twins supplement this. He carefully measured such brothers or sisters, both mentally and physically. On the whole they showed no greater resemblances as they grew older although subjected to similar training.

PHYSICAL HEREDITY IN MAN

There is a constantly increasing mass of evidence that man's physical and mental characters are transmitted in accordance with the laws of heredity that apply to other organisms. Of physical characters there is a long list that behave as simple Mendelian dominants. Such are brown eye color, brachydactyly (thumb-fingeredness), hexadactyly (six fingers and toes) symphalangy (a fusion of the second finger joints), lobster claw (a hand deformity), white forelock in certain families, piebald or spotted skin in colored races, congenital stationary night blindness, brittleness of bones, hereditary oedema (a swelling of body parts due to watery accumulations in the connective tissue), etc.

[1] Francis Galton, *Inquiries into Human Faculties*. Everymans' Library (1883).

[2] E. L. Thorndike, *Archives of Philosophy, Psychology, and Scientific Methods*, No. 1 (New York, 1901).

The brown color of the eye is due to the deposit of pigment in the outer portion of the iris. If this pigment is absent the eye is blue, due to the color of the inner portions of the iris. If pigmentation is entirely wanting the eye is pink, as in albinos, because then the blood-filled capillaries show. A brown-eyed person from pure brown-eyed parents will have in his cells a double dose of the gene for such eyes since he will have received one such from each parent. A similar homozygous blue-eyed person will have no gene for brown eye. If such a brown-eyed individual mate with the blue-eyed, the offspring will all be brown-eyed, since each fertilized egg must contain one gene for brown eye. But if such hybrid individuals (heterozygous for brown eye) mate, the children will probably be one fourth blue-eyed and three-fourths brown-eyed. There may also be present an intensity factor which produces the deep browns or blacks. Its absence permits the brown to be very dilute, giving a brown-blue, or gray eye. Apparently, too, there is a second factor for brown that is occasionally present and is sex-linked.

A striking example of the inheritance of night-blindness is recorded from a village near Montpellier, France. The affected person sees reasonably well by day, but is blind in dim light. Jean Nougaret, the original afflicted individual, moved to the village in 1637. For ten generations his progeny have carried the defect which behaves as a dominant.

Symphalangy or phalangeal anarthrosis (jointless fingers) occurs in several American families and is traceable for many decades. One Virginia family manifests the character for eight generations. The original American ancestor came from Scotland where the family also had the trait. An English family with the character still persistent traces it back through some 500 years to John Tudor, first Earl of Shrewsbury, who figures in Shakespeare's *Henry VI*. He was killed in battle in 1453, his skull being cleft and his thigh bone broken. Some 50 years ago his skeleton was exhumed by relatives, identified by the battle scars and incidentally the presence of this trait confirmed, a thing suspected

from the apparently stiff fingers portrayed on an old statue of him. (See Fig. 121.)

Such deformities as the last cited are relatively rare, and consequently two individuals each having the character seldom mate. However, in a village of the department of Isère, France, inaccessible much of the time because of the impassable character of the mountain trails, there developed through close inbreeding a population the great majority of whom were possessed of six fingers and toes. A similar phenomenon was found in the sequestered valley of the Aosta in northern Italy where a majority of the population was affected with goiter accompanied by imbecility and physical deformities. The government was forced to confine the more pronounced cases in institutions and to prohibit the intermarriage of such cretins to prevent further increase in their numbers.

There are many human physical characters that behave as recessives, as for instance albinism, left-handedness, deaf-mutism, congenital cataract, sensitive asthma. In the albino individual pigmentation is lacking or partly absent, and in consequence the skin is pale, the hair is very light, and the eyes are pink. If such a person mates with a normal individual all the offspring will appear normal, but will be heterozygous for the character. Such heterozygous individuals, mating, would expect three normal children to one albino. Two of the former would again be heterozygous. It is to be noted that in dealing with all recessive characters the heterozygous individuals appear to be normal. A large share of the population may bear the recessive character and the fact only becomes apparent when two such mate. Then one-fourth of their children may be expected to manifest the recessive character and will be homozygous for it, the genes for the normal condition being absent. Figure 122 illustrates this mode of inheritance.

Deaf-mutism may occur as a congenital defect, in which case it is manifest soon after birth, or it may be an acquired character produced as an after-effect of such diseases as meningitis or scarlatina. The latter type of deaf-mutism is not inherited. When

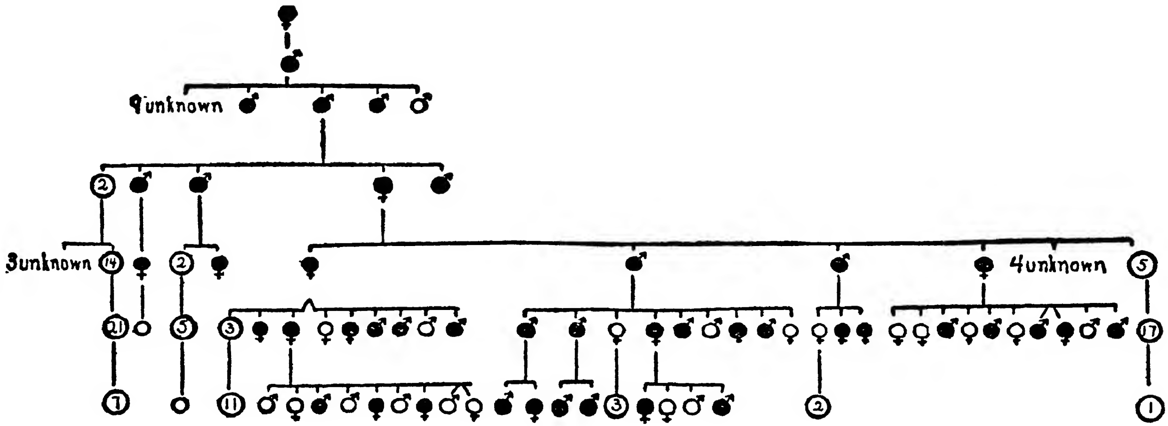


FIG. 121.—Pedigree of a line with brachydactyly, condensed and modified from Drinkwater's chart. It reads thus: A brachydactylous woman has a son, also brachydactylous. He has thirteen children, the condition of nine of whom is unknown; three possess the character; one is normal. One of these four known sons, himself brachydactylous, has six children. The sex of two is not known, but they were not brachydactylous; three sons and one daughter were. And so the family continues. One sees at a glance how the defect continues, generation after generation, not reappearing, however, in the offspring of those who are free from it.

deaf-mutes whose defect is due to such diseases intermarry, they will have children with normal speech and hearing. But when congenital deaf-mutes marry each other the children produced are all deaf-mutes. Thus Fay records a study of 22 families in which both parents were deaf-mutes from birth. There were 112 children in these families and all were deaf-mutes. In such cases the parents are homozygous, having no gene for the normal condition.

The tendency to tuberculosis and to most other diseases, in so far as there is evidence, is similarly a recessive. In the normal con-

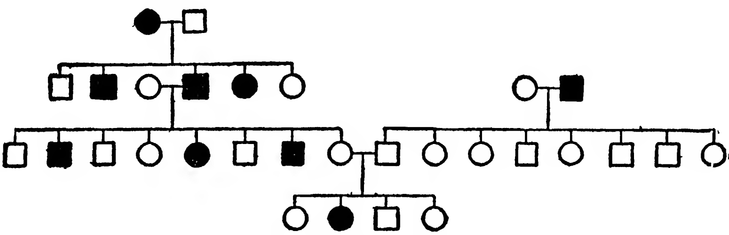


FIG. 122.—Left-handedness—a recessive character. Squares males, circles females. Left-handed individuals black.

dition there is a double dose of the gene for effective resistance. In some families this is lacking. A family showing, generation after generation, many cases of tuberculosis would be suspected of lacking this dominant gene. An individual without the gene, mating with a normal person, would have normal children, but heterozygous for the resistance gene. Two such heterozygous individuals would expect to have, on the average, one child homozygous for resistance, two heterozygous, and one without resistance, a pure recessive. Even such a susceptible individual can only have the disease when infected with the tubercle bacillus. Diseases as such are not inherited but one may fail to inherit resistance. Even in those cases in which children are born with tuberculosis or syphilis, the disease is not inherited but the fetus is infected from the parent before birth. In the case of the latter disease, since the uterus itself is the usual seat of infection, the birth of diseased offspring is common.

tion for the varying shades of color produced in crosses of the white and the negro races. Assuming that there are two factors for the dark skin of the negro, one more potent than the other, we would designate the full-blooded negro, as far as this character is concerned, by ***BB**BB*, the white by ***bb**bb*. The mulatto resulting from the cross would have a single determiner each of ***B*** and *B* and would be designated thus, ***Bb**Bb*. If such mulattos intermarry we should expect in a large number of the offspring that one-sixteenth would be as black and one-sixteenth as white as the original grandparents, and that there would be seven intermediate shades, that is, nine genotypes. The intermediates will be ***BB**Bb*, ***Bb**BB*, ***BB**bb*, ***Bb**Bb*, ***bb**BB*, ***Bb**bb*, ***bb**Bb*. Since in the order given there is a decreasing number of both heavy and light faced ***B***'s, the genes for the dark color, the possessors of these genes will be increasingly light. The white spoken of above refers only to skin color and does not mean that a Caucasic would result from a cross of mulattos. There would be light-skinned individuals as white as the white parents, but they would possess negro characters such as flat nose, thick lips, or kinky hair that would show their partial negro origin.

INHERITANCE OF MENTAL TRAITS

There seems to be good evidence that mental traits in man are also inherited, though we cannot yet tell the type of inheritance with the same degree of certainty as in the case of physical characters. Since half of the determiners in the fertilized egg are contributed by each parent, it would be expected that the correlation between the physical traits of a child and of either of its parents would be .50. This expectation is realized in a number of studies. Similar studies have been made of mental traits and the correlation is found to be about the same. Among the earliest of these were the investigations of Karl Pearson. They are being continued now with the more exact technique available for measuring and recording such mental characteristics and the results are in harmony with the earlier studies.

In the American biographical dictionaries there are brief life-histories of some 4,000 Americans of note. Since the average American family numbers five, we may calculate that each of these noted individuals has, on the average, 29 near relatives—3 children, father and mother, brother and sister, 6 nieces and nephews, 4 aunts and uncles, and 12 cousins. For the 4,000 individuals there would be 116,000 such relatives. Since there are 116,000,000 of us in the general population, the chance that any one of us may be a close relative of the noted individuals is 1 to 1,000. It is found, however, that one out of every five of these 4,000 noted Americans is also a close relative of some other one of the 4,000. It is evident from this that ability runs in families.

Galton, in his studies of the families of distinguished English judges, found in a similar way that the son of an English judge is 500 times as likely to be a person of note as the son of the average Englishman. A similar fact was disclosed in Galton and Schuster's studies of other "Noteworthy Families."

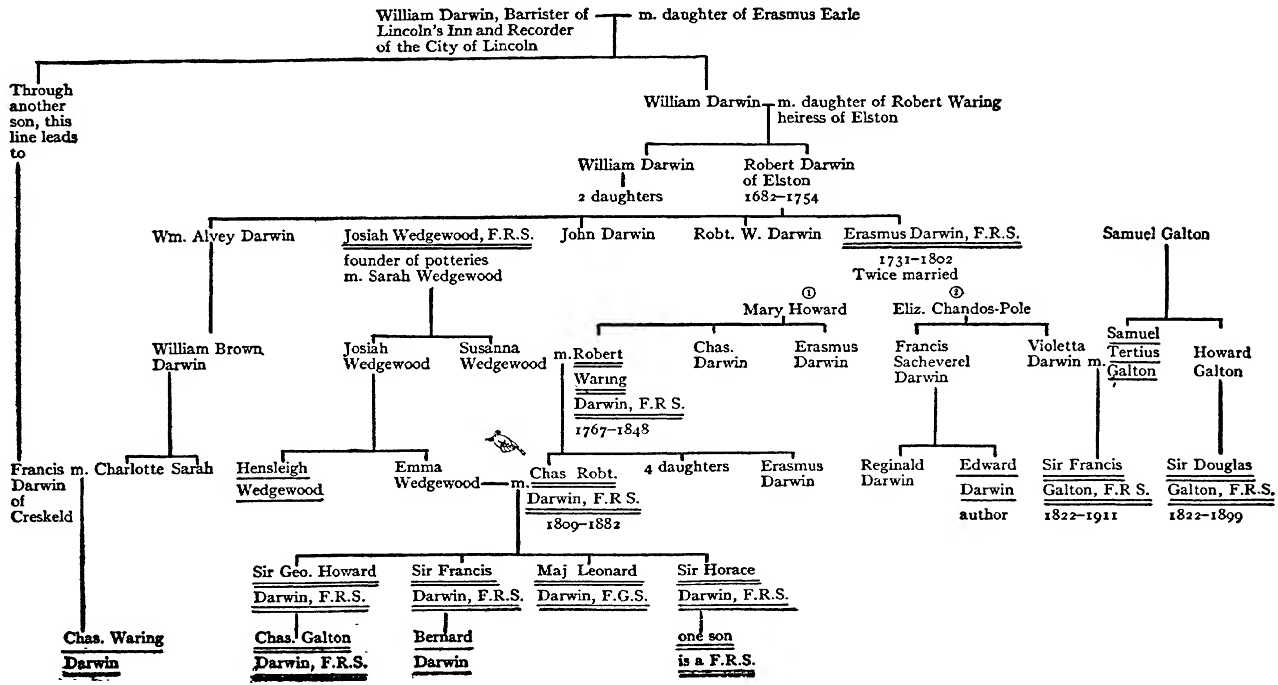
The family of Charles Darwin, diagrammed in Chart IV, will make the general statement concrete. Darwin's father was an eminent physician, a member of the Royal Society, as was also his grandfather. The latter was author of a treatise on evolution. Charles Darwin married his own cousin, Emma Wedgewood, whose grandfather was the founder of the famous potteries and himself a member of the Royal Society. Four of Darwin's sons are eminent and members of the Royal Society, as are also two of his grandsons. Darwin's aunt married into another family of note, and her son is Sir Francis Galton, the originator of the term "eugenics" and of the science that bears that name, founder of the eugenics laboratory named in his honor.

In the Bach family of noted musicians, of whom Johann Sebastian Bach is the best known, there were in six generations 47 musicians of repute, 29 of whom were really noted. In this case there was also much intermarriage. Johann Sebastian was twice married, each time to a Bach, and his father married an aunt. In two generations three pairs of brothers married sisters, not Bachs,

CHART IV

Pedigree of The Darwin, Wedgewood. Galton Families

(Able individuals underscored once, very able twice)



however. The close inbreeding in these two families seems to maintain the high character of a superior stock. There will be expected, of course, an occasional sporadic appearance of intellectual ability in mediocre stock due to the chance concentration in one individual of the desirable genes from several ancestors.

It seems equally true that the undesirable mental characteristics of dysgenic stocks are heritable. There is the famous, or rather infamous, case of the Max Jukes. A drunken ne'er-do-well called Max moved from New York City to the country, 50 miles away, taking with him a prostitute named Ada, both desirous of escaping the vigilance of the authorities. Others of loose morals followed and from this little colony of reprobates a progeny of over 2,000 has been traced by Dugdale and Estabrook. Over 600 of this number are feeble-minded, more than 300 paupers. There are 300 prostitutes in the lot, 140 criminals including 7 murderers. Not one of them has completed a common school education. Only 20 of them have learned a trade and 10 of these learned it in prison.

There is one striking family history that almost serves as a eugenic experiment. Martin Kallikak (the name is fictitious) just before the Revolutionary war had an illegitimate child by a feeble minded girl. She gave rise to 480 descendants that have been traced and all have been found subnormal in intelligence. Later this same man married a good Quaker girl. The progeny of this mating, so far as found, numbers 496 and all are of sound mentality.

Manifestly it is impossible to tell just how much of such transmission of desirable and undesirable characters is due to physical inheritance, and how much to the perpetuation of favorable or unfavorable home or other social environment. However, in Wood's studies of "Mental and Moral Inheritance in Royalty," it is shown that there is clustered about an able individual a group of able relatives, while mediocrity or inferiority is similarly related to the inferior individual. The environment of royalty is perhaps as little subject to variation as any and is uniformly favorable. It seems probable, then, that such striking contrasts as those between the

Darwin and Bach families, on the one hand, and the Max Jukes and Kallikaks, on the other, must largely be due to inheritance rather than to environment.

Goddard's extended studies of the feeble-minded have convinced him that feeble-mindedness is a recessive unit character, in spite of his preconceived notions to the contrary. He reports 42 cases in which heterozygous but apparently normal mothers (*NF*) mated with feeble-minded fathers (*FF*). Of 144 children produced, 71 were feeble-minded and 73 normal, almost exactly the expected

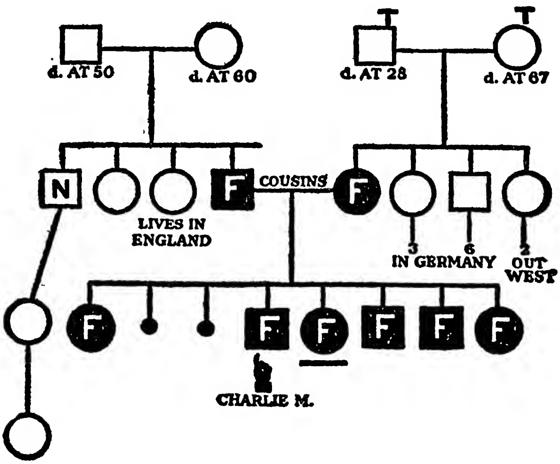


FIG. 123.—Inheritance of feeble-mindedness. Circles, females (small died in infancy); squares, males. (From Goddard's *Feeblemindedness*.)

Mendelian ratio. In 26 matings of heterozygous fathers and mothers (*NF*), 122 children out of 185 were known; of these 83 were normal and 39 feeble-minded. Of 476 children produced by matings in which both father and mother were feeble-minded, only six were normal in intelligence, and they were probably illegitimate. There is given here a typical pedigree of a feeble-minded individual. (Fig. 123.)

There seems to be considerable evidence that a tendency to insanity is inherited. Under the term insanity, however, is included such a variety of mental afflictions that until a large num-

ber of family records can be secured and these in exact terms, not much more than the general statement is possible. Huntington's chorea, a form of St Vitus dance with more or less of dementia, behaves as a dominant. Dementia praecox seems to be a recessive, but may be due to the interplay of two factors. Not infrequently a family manifests a variety of abnormal mental conditions such as feeble-mindedness, insanity, epilepsy, alcoholism, as if a degenerate stock were expressing its degeneracy in a variety of neuroses.

The burden of all these dysgenic elements in the population is heavy and is increasing. There are some 500,000 feeble-minded individuals in our population, of whom only about one-tenth are in institutions. These defectives comprise the idiots, with a mental age of 2 years or under; the imbeciles, with a mental age of 3–7; and the morons, with a mental age 8–12. The latter group only are designated as feeble-minded in some classifications. Probably 15 to 20 times as many persons as are feeble-minded carry the character as a recessive in their germ plasm without exhibiting it. These figures may not be as alarming as they seem, for 30.2 per cent of the white drafted men in the late war and 79.2 of the colored men had a mentality of 12 years or less according to the tests used. Yet they were not noticeably a burden in the general population. But from the feeble-minded group is recruited a large percentage of other undesirables. It is estimated that from 30 to 90 per cent of the criminals in penal institutions are feeble-minded. In a study of the inmates of the Georgia state prison made in 1919, 72.5 per cent were found to be feeble-minded. Goddard estimates that 50 per cent of the prostitutes are feeble-minded. At Newport News during the war, the prostitutes were under government supervision and 88 per cent were found to have a mentality of 11 years or less. In the United States there are 200,000 insane in institutions for their care, 150,000 epileptics, 165,000 criminals, and 80,000 paupers.

A British government commission, appointed for the purpose of investigating feeble-mindedness in Great Britain, recently re

ported its opinion that, during the last generation, feeble-mindedness has increased twice as fast as the population. Judging by the census returns in this country insanity has increased fourfold in the same length of time. Just how much of the apparent increase is due to better diagnoses and more accurate returns is not known.

It is to be noted that these dysgenic classes are largely eliminated among primitive races in the struggle for existence. Civilized man sees fit to set aside the law of the elimination of the unfit which in nature is an effective means of preventing racial deterioration among plants and animals. There remains, then, only one other means by which the character of the population can be controlled, that is through a regulation of the kind of individuals to be born.

The euthenist still expects to make many improvements in our environment. In fact, that is constantly being done. The laboring man of these United States is today better housed, better fed, and possesses more luxuries than the barons of the Middle Ages. His educational and social opportunities are incomparably superior to those of his fellows of earlier days. But the eugenist insists that we should not lose sight of the fact that such improvements are environmental and are not improvements of the human stock. That can be bettered only by selective mating. Education will enable the individual to realize more fully his potentialities, but its effects are not transmitted to his offspring through physical inheritance. Parents and offspring are of the same general stuff; both father and son are chips off the same block. The child starts where his parents started. A more favorable environment may help him progress faster and farther than they, but it does not, so far as we now know, change the nature of the germ plasm.

The farmer realizes that a good pasture will enable cows to give more milk than a poor one. But a limit is soon reached when improvements in the quality and amount of the feed produce no appreciable increase in the quality and amount of milk. For further betterment the character of the herd must be changed by breeding with a strain of cattle that gives a large and rich milk

yield. By such selective breeding, using as parents only those animals or plants that manifest the desired qualities in marked degree, and vigorously eliminating the low-grade offspring, man has worked wonders. He has produced the 200-egg-a-year hen, hogs that are veritable reservoirs of lard, cows that annually produce a thousand pounds of butter-fat, horses that do a mile in less than two minutes, corn that produces 100 bushels or more per acre, seedless fruits, rust-resistant grains. With such achievements before him, the eugenist is hopeful that man will attack the improvement of his own stock with as much intelligence and success as the animal and plant breeders have shown.

THE EUGENIC PROGRAM

What, then, is the eugenists' program? First, research. We must have more knowledge in regard to the modes of inheritance of human traits, whether they are inherited as dominants or as recessives, whether they are dependent on a single gene or on multiple factors, whether sex-linked or not, and a host of other details. There are several laboratories that are addressing themselves to these problems, such as the Galton Laboratory of England, the Cold Springs Harbor Laboratory in New York State,[1] the Volta Bureau at Washington. They must be multiplied and their efficiency increased. An intelligent public opinion must be brought to their moral and financial support.

The second item in the eugenist's program is education. The results of research must be made known to every man. The eugenist is optimistic and believes that Dan Cupid will submit to instruction. Such facts and laws of heredity as have been discussed in the preceding pages need to be passed on to the coming generation so that they may mate more intelligently. There is even now much eager and keen discussion of them. The eugenist is only asking at present that man shall use as good sense in the production of children as he does in the production of hogs or

[1] The Cold Springs Harbor Laboratory is desirous of obtaining family histories that will throw light on human inheritance. They will gladly furnish blanks and instructions for recording the same.

cabbages. That does not seem an unreasonable demand. A generation ago one might have taken a chance on marrying into a family displaying many cases of tuberculosis or insanity, for then next to nothing was known about inheritance. But now we know the inevitable consequences of such rashness. It is in the hope that youth, audacious and dutiful, will take to heart the teachings of heredity, that the eugenist undertakes his campaign of education. He regards Mendel as a seer and prophet, and the laws of heredity as a new revelation.

Third, it seems to the eugenist imperative that some means be used to check the increase of the dysgenic classes. At present segregation and sterilization are the devices in use to accomplish this end. Our efforts along both lines are sporadic and half-hearted. A portion only of the feeble-minded, epileptic, and insane are kept in institutions and many of these are frequently paroled to mingle with the general population and reproduce their kind. One feeble-minded man left at large in the early history of Ohio is known to have 75 feeble-minded persons among his living progeny. To segregate all the dysgenic individuals who are now undoubtedly such, and keep them securely in institutions for life, under conditions that will prevent offspring, would undoubtedly be temporarily expensive, but economical in the long run. Only an awakened and insistent intelligence, keenly aware of the menace of their increase, can assure such a desirable accomplishment. It is an open question as to whether such a policy of effective segregation would be even now any more expensive than the present ineffective methods. It would in all probability reduce crime and pauperism materially. We now spend eight times as much on the social machinery for protection against crime as we do for the education of our youth.

On January 1, 1926, there were 18 states that made mandatory by law the sterilization of certain types of persons, unfit for parenthood.[1] These states are California, Connecticut, Delaware,

[1] *Historical, Legal and Statistical Review of Eugenical Sterilization in the United States*. H. H. Laughlin. American Eugenics Society, 185 Church Street, New Haven, Connecticut.

Idaho, Iowa, Kansas, Maine, Michigan, Minnesota, Montana, Nebraska, New Hampshire, North Dakota, Oregon, South Dakota, Utah, Virginia, and Washington. In many of these states the present law is the third, fourth, or even fifth attempt to formulate a law that is both constitutional and administrable. Several other states have had similar laws that have been revoked by the legislatures or declared unconstitutional by their supreme courts. Possibly several of those now on the statute books will meet a like fate. But it is evident from such widespread and repeated attempts at effective legislation, that protection against the dysgenic classes by the method of sterilization is making headway. In all, 6,244 persons have been so sterilized under these laws in the United States. The operation required is simple and in no way endangers the health of the subject. It is to be hoped that out of the varied laws now in force, and future attempts at legislation, there may come a standard, uniform law, free from objectionable features and capable of just administration. The state of California leads in the number of sterilizations, with 4,636. The law in this state seems reasonably satisfactory and is functioning very well.

The fourth aim in the eugenic program is the production of larger families among persons of ability. One of the striking phenomena of modern times is the decline in the birth-rate in all civilized countries. Thus, the average size of the families in the United States was in the first half of the eighteenth century, 6.83; in the second half, 6.43; in the first half of the nineteenth century, 4.94, and in the second half, 2.77. This in itself is not alarming, but when it is realized that the decline is most marked in those elements of society that manifest the greatest ability and least marked in the distinctly inferior groups, it is a matter of grave concern. One might think offhand that if two parents produced two children it would be enough to maintain any stock. But allowance must be made for early death, infertility, failure to marry, etc. It has been calculated, taking such factors into consideration, that there must be an average of 3.7 children per family to

keep any class from decreasing. The Harvard or Yale graduate now has, on an average, 1.5 children; the Vassar or Bryn Mawr graduate, .7 of a child.

Dunlop gives statistics for Scotland on the number of children per family of various occupations, as follows:

Crofters (tenants farmers)	7.04
Miners	7.01
Agricultural laborers	6.42
General laborers	6.29
Ministers	4.33
Solicitors (law agents)	3.92
Physicians	3.91

True, there is a falling death-rate, and this also is differential, favoring the more intelligent classes. Thus, in the United States the average expectation of life was 35 years in 1870, but is now 58 years. The birth-rate in England and Wales fell from 36 per 1,000 in 1876 to 24 just before the war. The death-rate dropped from 23.7 (1864) to 14. But the differential of the death-rate does not offset that of the birth-rate. Thus in Philadelphia the following birth-rate and death-rate were prevalent in 1912:

	Birth-rate	Death-rate
In expensive residence districts	18. per M.	14.5 per M.
In well-to-do residence districts	21.4	....
American born factory workers	24.5	....
Lowest paid foreign born	41.9	20.5

It is impossible, on account of incomplete statistics, to state with certainty whether or not the differential drop in the death-rate, in the United States as a whole, offsets the drop in the birth-rate so completely as to permit the more desirable classes to maintain their numbers as compared with the inferior stocks, but in view of the data given, it seems highly improbable that they are so doing.

It is hoped that the realization of this situation will stimulate a sense of duty to the race on the part of the more able elements and bid the sacrifice on their part of social position, wealth, ease,

and luxury, for the sake of larger families. It remains to be seen if this effect will follow, but it is a possible refuge for the optimist.

Nations are experimenting with various types of legislation that have for their object an increase of the able classes. Increased taxation for bachelors, decreased taxes according to the number of dependent children, mothers' pensions, state bonuses for large families scaled to favor the professional groups, are samples of such devices that are being tried. The problem is exceedingly complex, for its elements are so tangled up with social mores, with economic wage problems, living conditions, educational and professional standards, war, immigration, and a host of other things that it will challenge the wisest statesmanship to devise ways and means of progress. Yet any farmer, from his experience with his herds and crops, would feel certain that the continued use as parents of inferior human stock instead of the superior would result in racial deterioration. We must find a way to produce not only a decrease in the undesirables, but also an increase in the desirable classes, or else the present civilization must give way to wiser peoples.

HYBRIDIZATION IN MAN

Immigration and the consequent mingling of the races in the melting-pot of America, together with the fusion of whites and blacks, presents a problem of great complexity. The eugenist wishes that he possessed sufficient accurate knowledge of the effects of racial blends to prophesy the outcome, or intelligently to direct its progress. Goddard found from the examination of 148 immigrant Hungarians, Italians, Jews, and Russians, at Ellis Island, that only two scored as high as 12 years on intelligence tests. It is evident that the admission of such inferior classes is detrimental. Eugene Fischer studied the effects of crosses between Boer men and Hottentot women in a hybrid population of 3,000. MacCaughey studied the effects of racial mixtures in Hawaii, Mjoen examined the results of crosses between Norwegian Nordics and Lapland Mongoloids, Lundberg investigated

hybrid races in Sweden.[1] In general, the conclusion is that while the first generation may show increased vigor due to the hybridization, succeeding generations manifest many physical and mental deteriorations that lead to early death, to crime, and to insanity. Admittedly, our knowledge of the whole problem is too limited to prophesy the outcome of particular crossings. It makes imperative immediate extensive studies to provide the information on which to base wise legislative control of immigration, and wise mating of the stocks already here. At present we are in the grip of hereditary forces, drifting toward a goal we do not know, powerless because of inadequate knowledge to direct our course in this matter of racial miscegenation. The challenge to the investigative energy, wisdom, and courage of the coming generation is apparent.

SELECTED REFERENCES

1. S. J. Holmes, *The Trend of the Race* (Harcourt, Brace and Co., 1921).
2. Popenoe and Johnson, *Applied Eugenics* (The Macmillan Co., 1924).
3. R. R. Gates, *Heredity and Eugenics* (The Macmillan Co., 1923.)

[1] Fischer's book was published in June, 1913; MacCaughey's article, *Journal of Heredity*, X, 1919; Mjoen, *Eugenics Review*, XIV, 1922; Lundberg, *Journal of Heredity*, XII, 1921.

*

CHAPTER XV

MAN FROM THE POINT OF VIEW OF HIS DEVELOPMENT AND STRUCTURE

GEORGE W. BARTELMEZ

I. EMBRYOLOGY AND EVOLUTION

Before the days of scientific zoölogy the turtle was regarded as a kind of bug and snakes were classed as worms. This was not without justification, for the distinctive backbone is not obvious in the living animal and the simple plan on which all vertebrates are constructed can be appreciated only after many laborious dissections. The innumerable variations in the details of the plan, on the other hand, are much more apparent, so that sharks, toads, snakes, birds, elephants, mice, and men seem very different from one another. If, however, we examine early stages in the development of different vertebrates, we are at once impressed by their resemblances (cf. Fig. 125). No one who can recognize the parts of the embryos, as the very immature young are called, can fail to understand why vertebrates should be included in one compact group. A comparison with the embryos of backbone-less animals (Figs. 77–78) makes this still more impressive.

The resemblances in vertebrate development are not confined to a single phase or stage of the process, but to the process as a whole. Indeed, when we study the earliest stages of development we find certain similarities not only among vertebrates but among all animals. Thus all sexually reproduced individuals begin their careers as single cells. Correlated with this is the fact that the ripening of the reproductive elements and their union in fertilization are fundamentally the same in plants and animals (p. 390). What do these facts signify? We regard them as evidence of kinship among all living things, even going beyond the Buddhist sage, who avowed relationship to "a worm in the belly of a most

mean beast." The argument involved in this induction of kinship is as follows:

The offspring of the individuals of a species tend to resemble their parents. The resemblances are not confined to the end-products of development, the adults, but to the process as a whole; nor are they confined to a single family but to all individuals manifestly related to one another, that is, to all members of a species. If we study earlier and earlier stages of development, the individuals appear more and more alike, for the characters that distinguish one adult from another will not yet have appeared.

Now, granting the general uniformity of natural processes, we must look upon the past history of any species as a succession of individual life-histories, each resembling that of its ancestors. The terms "resemblance" and "similarity" are significant, for no individual is ever exactly like either parent. Changes, be they gradually progressive or sudden, are always creeping into development as into other natural processes and such as are transmitted to the next generation (inherited) necessarily change the whole course of development to some degree, since they are inherent in the fertilized egg (zygote).

Had every change introduced into development in the past been preserved, we should see every animal rehearsing the evolution of its race. In the case of those species which have undergone innumerable and profound changes it is improbable that the detailed inheritance of the ages could be so condensed into the span of a single life. The process resembles rather that of our own memories which have preserved certain experiences with perfect fidelity but often show great and unaccountable lapses while they retain a wealth of trivial detail.

With these considerations in mind, we may conclude that fundamental similarities in the development of adults that differ greatly from one another indicate origin from similar ancestors. The greater the period that has elapsed since two stocks diverged, the greater the difference in the terminal products. This general-

ization was formulated by Ernst Haeckel in 1866, as his "Law of Recapitulation," which he stated as follows: "The development of the individual tends to repeat in an abbreviated and modified form the development of the race."

An example will serve to illustrate the law. A great majority of amphibians, even such as spend most of their lives in the water, breathe by means of lungs and skin. The larvae (tadpoles) of most frogs, toads, and newts live in the water and breathe with gills that are equipped with blood vessels essentially like those of fishes, which they resemble in many other ways. It is quite conceivable that this stage might have been omitted from development, for functional gills never appear in the development of other lung-breathing vertebrates, although they, too, always develop in a watery medium. Whether the young amphibian is hatched in the water, in the maternal oviduct, on the parent's back, or in the moist earth under a log, there is always a period when it has gills that serve to aerate the blood.

Many reverberations from the distant past have doubtless dropped out of development entirely. The wonder is that so many remain. Indeed in the development of the squid and octopus (p. 276) very few can be recognized. In other groups various adaptations to new conditions during development appear to have eliminated and obscured, as well as occasionally to have preserved, ancestral characters. It has been maintained (Peter) that no character of this kind persists which does not have a definite physiological rôle to play in the differentiation of the young animal. We shall, however, cite some structures characteristic of simpler vertebrates which appear for a few hours in the development of the human species only to disappear again without leaving a trace or giving evidence of having been of use (see pp. 453–54).

Before we can consider such details we must make a brief survey of vertebrate development and consider some of the modifications of the process that have appeared in the various groups.

WATCHING A DEVELOPING VERTEBRATE EGG

The transformation of the fertilized egg into an organism capable of a more or less independent existence may involve many weeks or even months, but, in some vertebrates, self-supporting larvae hatch out within a day after the fertilization of the egg. In such cases the changes are so rapid that one can sit for many hours enthralled by the beauty of the object and the orderly sequence of events as one structure after another appears. The egg is fertilized and after it has divided and subdivided and consists of many small cells instead of one large one, the primordial gut makes its appearance and anon the nervous system is separated. Soon the embryo begins to elongate, surface sculpturing can be detected, and presently an occasional pulsation can be recognized in the region of the future heart. By the time the red blood corpuscles are abundant, the heart is rhythmically pumping the blood through the embryonic blood vessels. Twenty-five centuries ago, when Aristotle studied hen's eggs on succeeding days of incubation, he could see nothing until the pulsating heart ("*punctum saliens*") had appeared. On this observation Aristotle based his doctrine of the primacy of the heart, which still persists in the traditional physiology of the poets. The establishment of the circulation usually initiates a more rapid rate of development. Muscles begin to twitch, and presently they are co-ordinated into effective movements as the nervous system establishes control over them. A new organism is before us, living, moving, and having its independent being. There is no better way to gain an appreciation of the marvelous potentialities of living protoplasm than to watch such an unfolding. It is most significant that at every stage of development the individual is an integrated organism; all of its parts are correlated and act together as a unit. Let us now consider some features of vertebrate embryology which are necessary for an understanding of mammalian development.

THE VERTEBRATE EGG

The differences between the eggs of the various groups are due largely to differences in the amount of accumulated yolk ma-

terial which serves as a food supply until the young animal can forage on its own account or until another source of nourishment is provided, as in mammals. The relative amount of yolk is largely responsible for the great difference in the size of the ripe egg, or ovum,[1] which usually tends to be spherical in shape. One of the smallest of ova is that of the mouse, which measures 0.08 millimeters in diameter in the living state (Kirkham) and is visible to the naked eye only under very favorable conditions. The largest that has been found belongs to a great shark and reaches a diameter of over 200 millimeters (Doflein). The hen's ovum is about 40 millimeters in diameter, while that of the frog measures 2 millimeters. The human ovum, on the other hand, grows to be only about 0.2 millimeters in diameter. The yolk material is usually laid down (during the period of growth in the mother's ovary) in such a manner that it lies chiefly at one pole of the cell—the vegetative pole. This is consequently different in appearance from the opposite, or animal, pole which after fertilization becomes the seat of much greater activity.

The relative amount of yolk in the ovum determines the mode of subdivision, or cleavage. If we take a hand lens and examine a frog's egg which has just been fertilized, we can clearly see the black pigmented region of the animal pole gradually fading out into the white, unpigmented vegetative hemisphere. Soon a furrow appears across the animal hemisphere, marking the beginning of the separation of the cell into two cells. It progresses much more slowly across the yolk-laden vegetative hemisphere, and very soon after the separation is complete, a second furrow appears like the first but at right angles to it. Both of the two cells have divided and we have a four-cell stage. Each of these in turn divides and so on for several hours. Early in the process, the divisions are much more rapid about the animal pole than in the vegetative hemisphere and the individual cells are therefore

[1] This refers only to the egg cell which is the so-called "yolk" of the hen's egg. Many other vertebrate eggs are also surrounded by envelopes such as albumen (egg-white) and a shell which represent secretions of the female reproductive ducts.

much smaller. Such a subdivision of the entire ovum is called a total cleavage. The eggs of many tailed amphibians are larger and richer in yolk than frog's eggs, and in them the cleavage furrows never reach the vegetative pole. Part of the original egg then remains as a mass of yolk which is not included within cells. (Cf. Figs. 125*B* and 127,*B* and *C*.) This is a partial cleavage. Now, in the relatively enormous eggs of sharks, reptiles, and birds only a small area at the animal pole undergoes subdivision in cleavage so that a disk of cells is formed. Under these conditions the early embryo is a thin membrane spread out on top of the great inert yolk mass (cf. Figs. 126 and 127, *D*), and as a result its body form is subsequently modified.

When embryologists began to look for evidence of relationship between reptiles and mammals, they were confronted at the outset by the contrast between the birdlike eggs of the former and the minute ova of the latter, which had been known since 1827 when they were discovered by C. E. von Baer, the father of modern embryology. Now, despite the reptilian characters of the monotreme mammals (duckbill and spiny ant-eater), the suggestion that they might lay eggs was promptly dismissed by those who had studied the adults most carefully. So in 1884, when a party of Australian scientists dug out a duckbill from its burrow and found a nest with manifestly reptilian eggs, the biological world was thrilled. It was soon found that the development of the egg is reptilian rather than mammalian in character. The ovum itself is 4 mm. in diameter at the time of fertilization and is covered with a layer of albumen and a shell. During its stay in the lower part of the reproductive duct (uterus) the yolk liquefies and the ovum imbibes secretions so that it increases more than ten times in volume. It is characteristic of mammalian eggs to swell up in this way. The development of marsupials like the opossum (p. 325) is much more like that of other mammals, but the eggs are nevertheless surrounded by albumen and a shell. They are well supplied with yolk material but are very small; the opossum's ovum reaches a diameter of 0.16 millimeters (Hartman) but after

fertilization it is smaller. During the process of cleavage (p. 444) a remarkable thing happens. Some of the yolk material is actually extruded from the cells, giving us direct evidence of a reduction of food reserves in the presence of abundant nutriment from the uterus. This phenomenon has also been observed in the eggs of certain bats which have eggs relatively rich in yolk. Although the monotremes still exhibit the partial cleavage of reptiles and birds, the minute eggs of all other mammals divide completely, giving us an excellent example of the relation between the amount of yolk and the type of cleavage. In mammals the process represents a secondary return to the total cleavage of primitive fishes and amphibians. Nevertheless, many features were incorporated into the development of the ancestral reptile-like mammals which have persisted and consequently we find that after cleavage the development of the mammalian ovum is reptilian rather than amphibian in type. The process of gastrulation offers an example of this.

Germ layers.—It has already been said (p. 188) that the process of cleavage is followed by a differentiation of three kinds of embryonic cells which are arranged in thin sheets called germ layers. The process is called gastrulation (bellykin formation) and it is never a simple infolding of the vegetative into the animal hemisphere as in many invertebrates. What we see, as we watch the living frog's egg, is the appearance of a narrow crescentic groove near the boundary between the hemispheres which has resulted from the infolding of certain cells into the interior of the ovum. Later on, the whole of the vegetative hemisphere is enveloped by an overgrowth of the more active pigmented cells of the animal pole. The black and white egg has become dark all over and we have before us a two-layered embryo, or gastrula. The entoderm later produces the mesoderm, and then we have an embryo composed of three layers of cells. In reptiles and birds, entoderm formation is followed by the appearance of an elongate structure called the primitive streak from which the mesoderm arises. It is an adaptation to the large mass of yolk in these eggs. The eggs of mammals have lost the yolk but still develop a yolk cavity within

a yolk sac and proceed to form an embryo much as reptile eggs do. A typical primitive streak always appears and produces mesoderm, giving us strong evidence for the reptilian ancestry of mammals. Figure 124*A* shows the appearance of a slice cut across a human primitive streak.

The germ layers that emerge from the process of gastrulation always produce the same systems of organs in vertebrates, and are of no small value in establishing homologies. The ectoderm gives rise, not only to the outer epidermis and its derivatives, such as hair and skin glands, but also to the entire nervous system and the sense cells of most sense organs. The entoderm furnishes the lining of the gastro-intestinal tract and its associated glands, such as the liver and pancreas. From the mesoderm come all supporting and connective tissues, including the notochord (p. 306), the heart with all the blood vessels throughout the body, the blood itself, the muscles, the excretory and reproductive systems, and the lining of the body cavity (coelom).

The formation of the nervous system.—To return now to our developing frog's egg, we find that before the process of gastrulation has been completed the nervous system makes its appearance as a thickening of the ectoderm about the animal pole. Soon we can recognize an elongated neural plate which is broader from the very outset at the end which will produce the brain. The plate is presently converted into a trough by the elevation of the sides, and we speak of neural folds inclosing a neural groove. They are naturally broader and higher in the brain region, where they show a distinct beading. The neural tube is formed after the folds have risen to a certain height, approached one another, and then met in the midline. The adjacent skin, which has also been lifted up, fuses across the seam and so the nervous system becomes an internal organ. Its tubular condition persists throughout life. The closure of the neural folds is a gradual process. In man, it begins at the boundary between the future head and neck and extends both forward and backward. If, then, we select the proper stage of development we can see all transitions from neural plate to neural

tube in the same embryo. Such a series is shown in Figure 124, which presents photographs of thin slices across the body of a young human embryo at different levels.

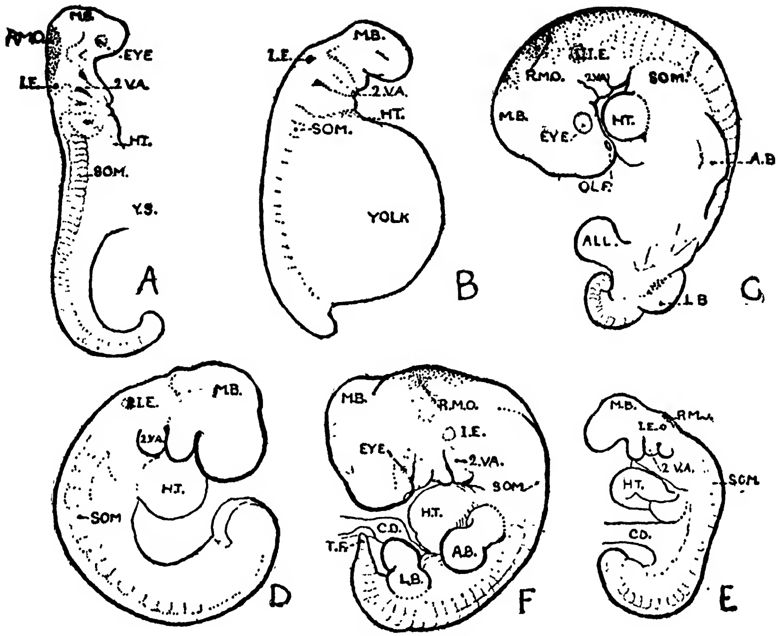
While the nervous system is forming, the mesoderm has begun to divide into a series of blocks which give us the first clear evidence that the vertebrates were originally built up of a longer or shorter chain of segments, each similar to the others. The mesodermal blocks, or somites, enter into the development of the hinder end of the head, the entire trunk, and the tail. From them come bones, such as the vertebrae and ribs, as well as muscles which show a distinct segmental pattern in the adult. Each has a segmental nerve associated with it and between each two a branch grows out from the great blood vessel called the aorta which distributes the blood from the heart throughout the body.

The somites are characteristic features of all young vertebrate embryos and this is true also of the bars or arches which carry the gills of fishes and larval amphibians. In the higher vertebrates the embryonic gill arches are as well developed as in the lower. Between each two arches there is a projecting pocket of the embryonic pharynx, called a gill pouch. Now the foremost pair of gill arches meeting its mate in the midline gives rise to the upper and lower jaws, which are present in all vertebrates above the lampreys and hagfishes (cyclostomes). The first gill pouch is converted into the middle ear of all air-breathing forms and it is, therefore, easy to see why it should always appear in development. But the second gill pouch never seems to have any particular part to play in reptiles, birds, and mammals, and yet it is always well developed. The obvious explanation is that this region of the pharynx develops as it always has since the ancestral vertebrates appeared; the past repeats itself in the present. In man certain structures arise within the first and second visceral pouches which resemble rudimentary gills in form. Although they are close to large blood vessels they seem to have no blood supply and they persist only for a very short time early in the fourth week of development, leaving behind no trace.

We may turn now to Figure 125 which presents enlarged portraits of several vertebrate embryos. The resemblances are obvious if we consider the gill arches, the somites, the heart, and the brain in their mutual relations. The great size of the head is largely due to the early development of the brain. The sharp bend which marks the midbrain (*M.B.*) can be recognized in every case. The heart is at the hinder end of the head, where it remains throughout life in all fishes.

Before we can consider the fundamental plan on which all vertebrates are built and, by a study of thin slices through the body, see the relations of various internal organs, we must turn aside for a few moments to review the formation of the embryonic membranes, or envelopes, which characterize the higher vertebrates ("amniotes").

Embryonic membranes.—The embryos of fishes and amphibians are naked except for surrounding jelly-like substances and shells such as are provided by the maternal genital ducts. Bird and reptile embryos have a highly efficient protection of this sort, but in addition, the embryo itself produces certain enswathing membranes as well. As we have seen, it is always spread out on a great yolk mass toward which the intestine is open for a long time (Fig. 126 *A*). In amphibians, on the other hand, the yolk-laden cells of the vegetative pole form the floor of the alimentary tract which is completely inclosed by the ectoderm. In Figure 127 *C* we see the primitive relation of yolk included in the cells of the gut lining. In Figure 127 *B*, where there is relatively much more yolk, we have a transition to the conditions in reptiles and birds diagrammed in Figure 126 *A*. In these groups the entoderm and mesoderm, which form the wall of the gut, spread out over the yolk mass, developing blood and vessels that serve to carry the digested yolk to the embryo and, what is equally important, to absorb oxygen. Thus a bag surrounding the yolk mass is formed, called the yolk sac (*y.s.*, Fig 126 *B*, *C*, *D*). Now in mammals, despite the insignificant supply of yolk, a typical yolk sac develops and accumulates fluid so that it becomes large compared to the



KEY TO FIG. 125

FIG. 125.—Enlarged portraits of some vertebrate embryos in similar stages of development reproduced without retouching. *A*, a shark (*Mustelus*), ×8. *B*, a tailed amphibian (*Cryptobranchus*) enlarged to 6 diameters from a photograph by Dr. Bertram G. Smith. *C*, a chick of about 3½ days' incubation, prepared by Miss D. Brocket, ×10. *D*, a rat, 10½ days after fertilization, ×25. *E*, a human embryo, H984 belonging to the Department of Anatomy; about 3 weeks old, ×12. *F*, a human embryo, H1027 from the same collection about 6 weeks old, ×5. This presents a more advanced stage than any of the others.

The same fundamental structures with the same relation to each other can be seen in each case. The most striking differences are in the extent of the various bendings or "flexures" of the body and head. Minor differences are seen in the degree of development of certain parts in the different species. In the shark, the gill region is very prominent and the first two pouches have opened to the exterior. The eye primordium has made further progress than in any of the others except *C* and *F*. The shark is further characterized by having many more segments than the others and the somites are long and narrow. In the amphibian as in the shark, the heart is, as yet, feebly developed compared to other parts. In the chick the brain is very large in proportion and the limb buds have already appeared. The rat and the younger human embryos are very similar although the latter has 22 as compared with 14 somites. In the older human embryo (*F*) only the first two arches are visible as the others have been overgrown by a fold of skin. The limb buds are in the "paddle" stage and there is an obvious tail filament, just behind the umbilical cord (*Cd.*) which serves to unite the embryo to the nutrient placenta. It is in the same general position as the allantois (All.) of the chick (*C*).

A.B., arm bud; All., allantois; Cd., cord uniting embryo and placenta; Eye, eye rudiment; I.E., inner ear rudiment; Ht., heart; L.B., leg bud; M.B., mid brain; R.M.O., thin roof of medulla oblongata; Som., somite; T.F., tail filament; Y.S., yolk sac; 2 V.A., second visceral (gill) arch.

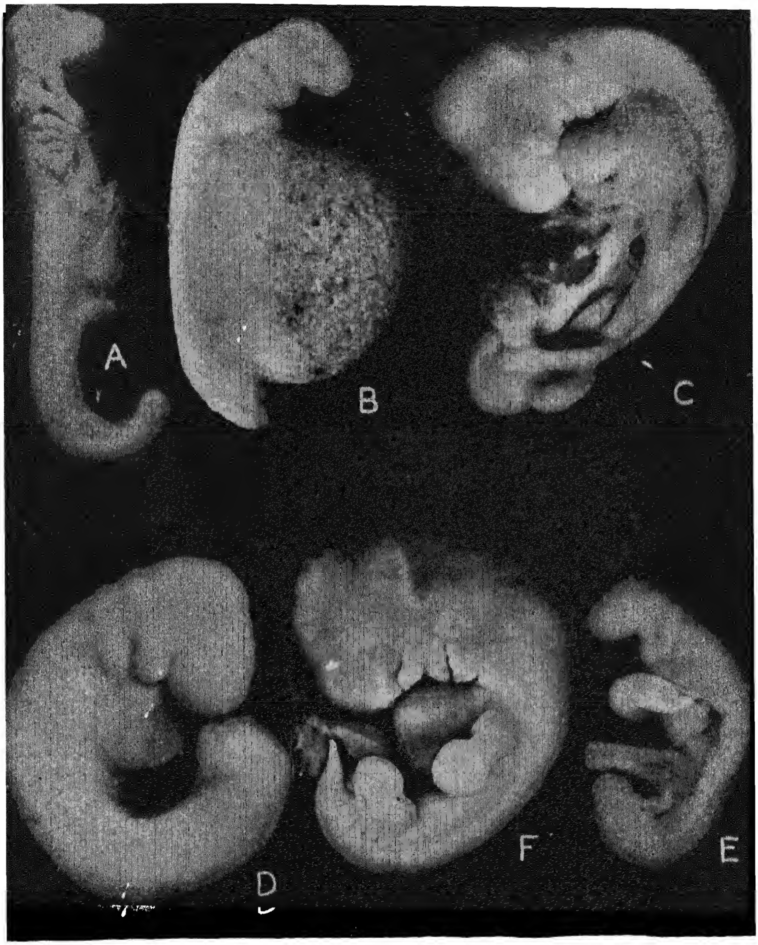


FIG. 125.—In *B* alone the entire specimen is shown. In the others the yolk or the yolk sac has been removed.

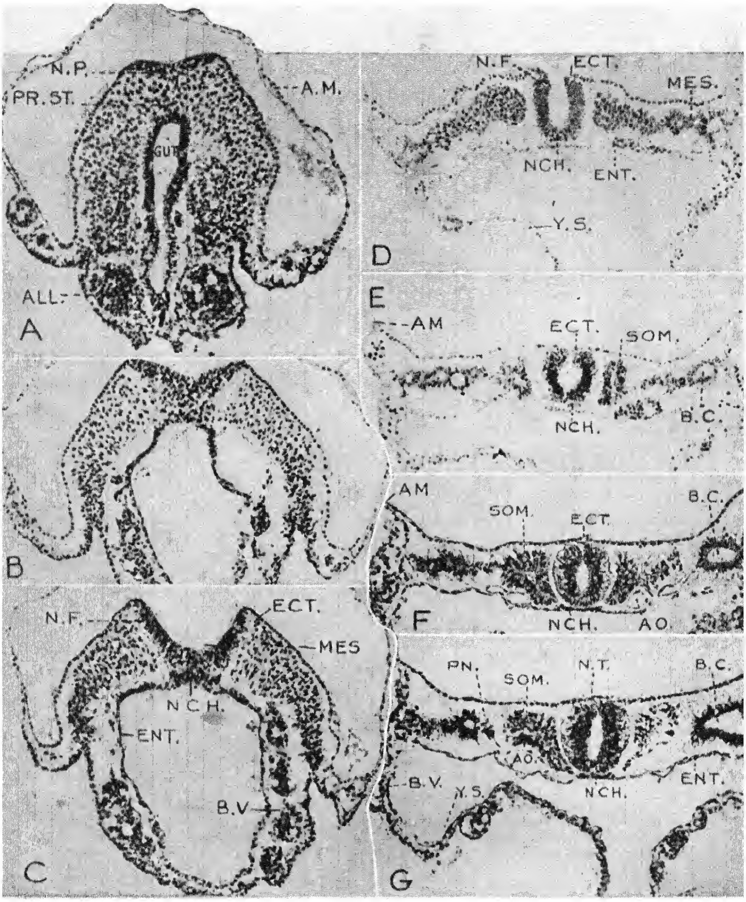


Fig. 124.—A series of microphotographs from thin slices cut across the body of a three-weeks-old human embryo, magnified 80 diameters, Embryological Collection of the Department of Anatomy. The slices are taken at different levels beginning at the hind end and show stages in the formation and closure of the neural tube. *A* shows the primitive streak (see p. 447) where the neural plate is already foreshadowed by the closely crowded nuclei each of which appears as a black spot in the figure. In *B* there is a shallow groove in the neural plate and in *C* we can speak of neural folds. *D* shows the rapidly approaching neural folds and in *E* the ectoderm of the outer skin has fused over them but the folds themselves have not yet united. The seam of junction still shows in *F* but in *G* we have a closed neural tube.

All., allantois; Am., amnion; Ao., aorta; B.C., body cavity; B.V., blood vessel; Ect., ectoderm; Ent., entoderm; Gut, primitive gut; Mes., mesoderm; Nch., notochord; N.F., neural fold; N.P., neural plate; N.T., neural tube; Pn., rudiment of primitive kidney; Pr. str., primitive streak; Som., mesodermic somite; Y.S., yolk sac.

embryo, which lies spread out on top of it precisely as in reptiles and birds. This is clearly shown in Figure 124 *D*, which presents the conditions in man. The human yolk sac is important in the early formation of blood and it reaches a size of 5 or 6 millimeters.

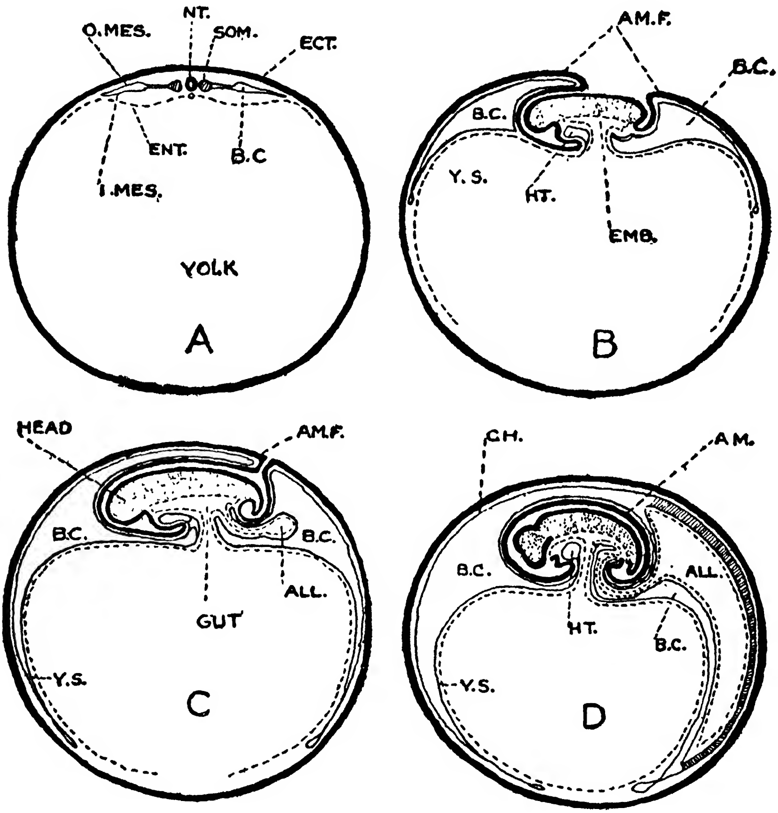


FIG. 126.—Diagrams based primarily upon the bird's egg to show the relations of embryo to the yolk mass (*A*) and the development of the embryonic membranes (*B*, *C*, *D*). *A* represents a cross-section of a young embryo, the others longitudinal sections of progressively older ones. Slightly modified from Grosser (1909).

All., allantois; Am., amnion; Am.F., amniotic fold; B.C., body cavity; Ch., chorion; Ect., ectoderm; Ent., entoderm; Emb., embryo; Ht., heart; I.mes., inner layer of mesoderm; N.T., neural tube; O.mes., outer layer of mesoderm; Som., somite; Y.S., yolk sac.

Two characteristic membranes, the amnion and chorion, are formed by a folding of tissue round about and up over the body of the embryo, as is indicated in Figure 126 *B, C, D, AM.F., AM., CH*. The amnion is filled with a watery fluid that encompasses the whole embryo. Thus all amniotes (reptiles, birds, and mammals) exist in an aqueous medium until the time of hatching or birth (cf. p. 442).

The yolk sac does not long remain the embryonic respiratory organ, but is replaced by an outgrowth of the gut which corresponds to the urinary bladder of amphibians. In some mammals it may resemble a sausage, and has accordingly been termed the allantois (Fig. 126, *ALL.*). It is just beginning to balloon out in the chick embryo shown in Figure 125 *C*. Spreading out between amnion and chorion in the coelomic cavity, it comes to lie in contact with the chorion (*CH*). In mammals the chorion and allantois play a major part in the formation of the organ called the placenta through which nourishment for the young is taken up from the mother's blood.

The vertebrate ground plan.—Let us now consider the relations of the fundamental systems of organs in vertebrates as we see them in thin cross-sections of young embryos (Fig. 127). Beneath the skin in the midline of the back is the tubular nervous system (*N.T.*) with the notochord (*NCH*) below it. The gut (*G*) is in the midline underneath and may be spread open on the yolk (or its fluid representative in mammals) which is surrounded by the yolk sac. On either side of the nervous system is a somite or segment of the middle germ layer (*SOM.*), and lateral to this again is the tubule of the primitive excretory organ (*PN*). In every vertebrate embryo these parts are present and have the same relationship to each other. The body cavity arises somewhat differently in different forms, but its walls always have the same structure and relationships.

Since the general features of man's development are nowise different from those of other vertebrates and since they are like those of other mammals in innumerable details, we need no fur-

ther evidence of his kinship with them. Evidences that changes in development are still in progress should be noted. Such are furnished by vanishing, or vestigial, structures.

Vestigial organs.—We shall confine our attention here to certain ancestral reminiscences in human development which appear to be gradually dropping out, for they do not seem to appear in every individual and certainly do not always appear at the same stage in every case nor are they always equally well developed. One of the best examples is found in the development of the communication between the neural groove and the primitive gut, the neurenteric canal, which arises during the process of gastrulation at the upper end of the primitive streak. We see it in its typical form in reptiles, but it has disappeared from the life-history of most mammals. It is a prominent feature of certain three weeks' human embryos, but is absent in others of this stage of development. It probably never appears in some individuals; in any case it persists for only a few hours. No one has ever suggested a function for it and it does not give rise to anything.

The third eyelid, or nictating membrane, of the eye is another example. Unlike the upper and lower lids, it is a characteristic vertebrate structure which reaches the height of its motility and functional importance in birds and is prominent in most adult mammals, including many monkeys. It appears and develops in the usual manner in human embryos, but later it regresses, leaving only an inconspicuous fold (the *plica semilunaris*)at the inner border of the eye. A similar story might be told of the primitive or "head kidney."

It has been pointed out that the allantois (p. 452) arises as an outpouching of the hinder end of the gut in higher vertebrates (amniotes) (Fig. 126, *ALL.*). The outer (mesodermal) part of it appears very early in human development and is important in establishing the connection between embryo and nutrient placenta. The actual outgrowth from the lining of the gut (entoderm), on the other hand, is very small and persists usually for a brief period. An early stage is shown in Figure 124*A*. Rarely it

may develop an expansion at its end, but we never see a great sac as in Figure 125 *C* or 126 *C* and *D* (*ALL.*). It, too, seems to be a dim and fading "memory" of the past in human development.

There are other organs which make their appearance normally but are so little used that they subsequently atrophy. Outstanding examples are the muscles of the external ear, which are highly important and well developed in most mammals, and the vermiform appendix, which is homologous to a large digestive pouch in other groups of mammals.

Microscopic structure.—It may be added that the resemblances between man and all other vertebrates are not confined to the general plan of structure and to a superficial similarity of parts in relations and form. The very cells of the stomach, the liver, the kidney, etc., in the adult are always remarkably similar in their form and structure. When we examine the organs of invertebrate groups, which have the corresponding function, we usually find that their minute structure is very different from anything in vertebrates. Similarity in function, then, will not account for the resemblances in any group; they can best be explained on the basis of an origin from a common stock.

We may say, in conclusion, that man is a perfectly typical vertebrate and that his parts are generalized rather than specialized. Thus he has the two pairs of limbs, structures which have either completely or almost completely disappeared from snakes and other highly specialized forms. He has five fingers and toes, although in the majority of mammals they have undergone more or less reduction in the course of evolution. He has not the great size of many decadent stocks. He lacks only one part which may be considered as typical of the whole group—an obvious tail which, however, always appears in development (see Fig. 125 *F*, *T.F.*). Only a single fundamental organ has undergone great specialization in the genus Homo. This is the brain. It is the only structure which can be called hypertrophied by comparison with primitive and generalized vertebrates. We may turn now to a consideration of this distinctive organ. In order to do so we must

briefly discuss the nervous system in general, building the foundation for an understanding of the particular parts of the brain which anatomically and physiologically distinguish man from all other animals.

II. THE NERVOUS SYSTEM

THE NERVOUS SYSTEM IN GENERAL

Irritability is one of the fundamental properties of protoplasm. External forces impinge upon the living substance and initiate changes which spread through it and modify its other activities. There are good reasons for believing that this responsiveness to stimuli plays a large part in making an integrated individual out of a mass of protoplasm or a group of cells (Child). It must be remembered in this connection that the protoplasmitesimal *Amoeba*, a seeming speck of jelly, is a living animal, capturing its food, avoiding danger or escaping from it as successfully as higher animals do.

In some of the large and highly specialized unicellular animals there are distinct paths in the protoplasm for the transmission of impulses, and this foreshadowing of a nervous system can easily be followed to the simpler many-celled animals (Parker). Sense organs especially responsive to definite kinds of stimuli seem to have been the next step in evolution. Then certain nerve cells gathered together in one place as a central nervous system which served to receive and correlate the impulses from different sense organs and to co-ordinate the activities of organs like muscles, insuring their mutual co-operation. In these primitive forms, where the behavior is so simple that it can be fairly completely analyzed, it is clear that the nervous system is the material basis for the behavior, and the range of variability in behavior is in direct relation to the complexity of the structure in the nervous system, which thus serves to adapt the animal to its environment.

In a striking passage Herrick has contrasted the reactions of a daisy, a bee, a plowboy, and an artist to the same environment and pointed out the part which the organization of the nervous

system, or the lack of one, plays in the potentialities of adjustment and behavior in each case.

FUNDAMENTAL STRUCTURE OF THE NERVOUS SYSTEM

Like other bodily organs, the nervous system is built up of two types of cells, those which are highly specialized in structure (nerve cells) for performing specific nervous functions, and those which serve to support the nerve cells and to carry nourishment to them. The nerve cells are characterized by their branched processes which extend out from the mass of protoplasm ("cell body") surrounding the nucleus. One of these processes is relatively very long and slender (the axone) and it alone serves to carry impulses away from the cell body, while the other processes, called dendrites because they resemble the branches of a leafless tree, conduct impulses toward it. Thus impulses gathered by the dendrites are transmitted to the cell body and are then conducted to other cells by the axone. According to the best substantiated theory, nerve cells may become very large and complex and they have accordingly been called neurones. There is adequate evidence, for instance, for believing that the axones which conduct nervous impulses to the muscles of the foot, causing them to contract, are protoplasmic cell processes which reach a meter's length in man. There are other neurones concerned in carrying impulses from the joints and tendons of the toes, which, in addition to the meter-long peripheral process, have another which runs up to the brain and is 0.6–0.7 meters in length. These are the giants of their tribe, to be sure. The figures become impressive when we consider that most tissue cells are invisible to the naked eye. The neurone nevertheless displays some of the most characteristic reactions of a single cell. It behaves precisely like a one-celled animal when mutilated. If the injury is severe it will eventually die, but the part which is cut off from the cell body, where the nucleus is, will die much sooner than the other. Within a day or two after a process has been injured the cell body will show the effects of the mutilation though this be far removed The part that has

been separated from the cell body is doomed to destruction. A fact of great practical importance is that the neurone can regenerate a lost part, restoring its function, provided only that the severed part is not too great in proportion to the whole and that it is outside of the central nervous system. Thus an injury to a nerve supplying a muscle or an area of skin may be fully repaired in time. On this fact are based some of the greatest triumphs of modern reparative surgery.

The vertebrate nervous system.—We must turn now to the parts of the nervous system as we see them in vertebrates. The fundamental division here is between sense organs and a central nervous system, for the connection between the two is established for the most part by nerve cells which have wandered out of the neural tube early in development. All neurones or neurone processes which lie outside the central nervous system in the adult are included in the peripheral nervous system. It therefore involves: (1) Sense organs, (2) conducting nerve cells which carry impulses from the sense organs to the central nervous system (sensory neurones), and (3) processes of neurones which carry the behests of the central nervous system to organs like muscles (motor nerve fibers). Thus, in addition to the sense organs, the peripheral nervous system consists of nerves, which are bundles of processes from various kinds of neurones, and also of groups of neurone cell bodies, called ganglia, scattered about in various parts of the body outside of the central nervous system. The cell bodies of sensory neurones, for example, usually lie in ganglia. The central nervous system is compact nervous tissue where (1) different kinds of impulses are brought together so that they may reinforce or counteract one another in sensory centers; where (2) the activities thus initiated may be carried to motor centers that maintain control over muscles, blood vessels, etc., co-ordinating their activities. A concrete example will clarify this. The barbels of a catfish are supplied with sense organs of taste and touch. They are trailed over the bottom and when they come into contact with a worm, the fish usually turns and snaps it up. The same

behavior follows the touching of a bit of absorbent cotton soaked in meat juice. This is, however, promptly ejected and not swallowed like the worm. On the other hand, plain cotton evokes no reaction since the two types of stimuli are usually necessary to produce it. Behavior of this type is dependent on a central nervous system, which gives us a mechanism for physiological choice, i.e., a selection between alternate responses (see Herrick, *Brains of Rats and Men*, chap. iii). Such nervous activity takes place in a part of the central nervous system which appears gray in the fresh condition (gray matter) in contrast with the "white matter" which is made up only of axones and serves merely to conduct nervous impulses from one region to another. In the gray matter, neurones come into physiological relation with one another; the contacts between them are called synapses. Since a given neurone may have direct synaptic relations with many others, its activities may be controlled by many factors. The more complex the behavior of an animal is, the more numerous and intricate are the synapses in its central nervous system.

According to the neurone theory, neurones are merely in contact with one another at the synapses, that is, the dendrite of one and the axone of another have the same relation as two conducting wires which simply touch each other. If they were soldered together, as some believe, it would be much more difficult to understand, for example, how the same neurone may make different kinds of functional connections in rapid succession, how it can be a part of one "reflex arc" (pp. 481) now and of another later, and how a neurone may be activated through one synapse, restrained from acting by another. We know that there are synapses of various kinds on the same cell. Every "nerve cell" (the cell body and dendrites) is surrounded by a thick felt-work of branching axones carrying impulses from other cells. These axone terminations may wind about a dendrite as the ivy entwines the oak. There are other synaptic endings which look like small knots pressed against or into the sides of the cell body or dendrites. Both types of synapse are shown in Figure 23 *G.*

Some of the most striking synapses look like a wilderness of intermingling branches denser than a hawthorn thicket.

It is obvious, from what we have said, that one neurone cannot accomplish anything by itself. It must come into functional relation with at least one other. The response to a stimulus involves two or more neurones physiologically united for the time being into a chain. This functional unit of the nervous system is called a reflex arc, and is discussed at length in chapter xvi. Let us turn our attention now to the various parts of the central nervous system.

Parts of the central nervous system.—We always find certain subdivisions in the vertebrate central nervous system which are reminiscences of a primitive segmental structure. Its distinctive feature, however, is the mechanism for spreading impulses from one part to another, and as a result it is much more efficient in integrating the activities of the body as a whole than it ever becomes even in the highest invertebrates (insects), where each segment tends to be independent and self-sufficient (Herrick, 1922, p. 29). Most of the vertebrate segments are blotted out early in development by bundles of axones which run longitudinally through the central nervous system bringing its parts into functional relation with one another. Certain segmental boundaries persist, however, and they serve to mark off the following parts which we call subdivisions. We can recognize:

1. A spinal cord, inclosed within the vertebral column, which is immediately concerned with the activities of the trunk and the limbs. It contains the machinery for their inborn reflex reactions. Normally it is under the direct control of higher centers, but it may act independently even in human beings.

2. A brain, which in mammals completely fills the dome of the skull. The brain and its bony case develop *pari passu* and are accordingly directly correlated as to size and shape. Those particular segmental divisions which persist throughout development are found in the brain. Each division has come to be dominated by some definite sense organ or the like and has probably re-

mained distinct for this reason. This must have occurred early in vertebrate evolution, for it is an astonishing fact that the same segments can be recognized in every vertebrate species. In embryological origin, in structure, in function, they are fundamentally the same throughout the groups. The very neurones of certain segments and even their synapses are always similar in form, so that in different vertebrate classes the neurones may be as much alike as are different species of poplars or oaks.

As we must devote most of our attention to that brain segment which is the distinctive anatomical characteristic of man we shall merely enumerate the others. Their relations are shown in Figures 128 and 131. Beginning with the hinder end, which is continuous with the spinal cord, we have:

a) The hindbrain (*HB*), which has much the same relation to the head as the spinal cord has to the rest of the body. In this connection it must be remembered that the heart and lungs, as well as the gill region, belong phylogenetically and embryologically to the head. Hence the hindbrain has important centers for the control of the heart and lungs. It is divided into two parts: the medulla oblongata and the cerebellum (*M.O.* and *CBL.*). The latter is primarily concerned with the adjustment of the body as a whole to its position in space. The more active an animal is, the larger is its cerebellum. Thus fishes and birds that move in three planes of space have large cerebella, while in newts and lizards, which crawl about on their bellies, this division of the brain is minute.

b) At its upper, or cerebellar, end the hindbrain passes over into the midbrain (*M.B.*), which is related primarily to vision and hearing.

c) The terminal end is the forebrain (*F.B.*), and this "growing tip" is the region of greatest potentialities. Primitively it is dominated by smell, but in all vertebrates it has other centers where impulses elaborated at lower levels are brought into relation with one another. Many different kinds of impulses from different parts of the nervous system are concentrated here and the op-

portunities for correlation are exceptional. It can at any time assume a dominant control over the rest of the nervous system.

The brain is like every other vertebrate organ in that its fundamental plan is the same in different vertebrates, though there is great variation in detail. And this variation can always be correlated with differences in behavior. We may cite but a single case. In most vertebrates the centers for taste in the hindbrain are inconspicuous. Catfishes and their relatives find their food chiefly by the sense of taste, and the organs of taste migrate out of the mouth during development, not only onto the barbels but also over the skin of the body and tail. The brain center to which the taste impulses are carried is not only enormous, relatively, but complex in structure (cf. Herrick, *Introduction to Neurology*, Fig. 139). Obviously, the great taste centers in this brain are directly related to the importance of taste in the animal's behavior. Such responses and much similar activity of the brain and spinal cord are as mechanical as the working of an automatic telephone exchange. A definite stimulus has a definite effect, like the "batting" of the eye before one is conscious of danger. Other reflex mechanisms are discussed in chapter xvi. They are inherited mechanisms concerned with responses which do not have to be learned and which are, on the whole, advantageous to the individual under normal conditions. Such activities reach their height in the most complex of invertebrates, the insects. Vertebrates, on the other hand, have developed in a different direction. As we go up the scale, we find a gradual increase in the ability to adapt to new conditions, to solve problems, to profit by experience, and hand in hand goes an increase in the relative size of the forebrain. Even the fish has forebrain centers competent to deal with new situations. If its automatic feeding reactions are interrupted by the stimulus of a fish-hook concealed in a delectable morsel, the behavior is abruptly changed. The forebrain appears to assume control, impulses are sent widely through the nervous system, and a violent and often a cunning struggle for life may ensue. Forebrain activities are clearly concerned with the highest types of adaptive

behavior. In no other species do we find so complex a behavior nor so large and intricate a forebrain as in man. We may now consider the particular part of the forebrain which is hypertrophied (greatly enlarged) in his case.

The development of the human cerebral hemispheres.—Early in the study of human development (Tiedemann, 1826) it became clear that one of its most distinctive features is the tremendous growth of the terminal end of the central nervous system. We know now that this growth involves the very tip of each neural fold (p. 447), but it is not until some time after the closure of the folds that the cerebral vesicles balloon out from the end of the neural tube, one on either side (Fig. 128), and develop into the cerebral hemispheres. At first they are insignificant in man, as in other vertebrates, and they remain in an embryonic state long after the reflex centers are functional. As we shall see, they are not yet functioning at birth. As hollow buds of the neural tube, the hemispheres have cavities continuous with those of the other brain regions and they remain hollow throughout life.

A most important feature is that, unlike many other parts of the brain, the gray matter with its neurones and synapses is on the outer surface of the cerebral vesicle where its growth is unhampered by pressure from surrounding parts. This superficial gray matter is called the cerebral cortex. At first the walls of the cerebral vesicle are thin, and with its gradual expansion they mushroom out over the rest of the brain, finally covering up all else and extending far in front of the original terminal end of the nervous system. This may be seen in Figure 128 where the cerebral vesicle is marked by coarse stippling. We see that at first the vesicle is terminal and dorsal in position. Then it spreads in all directions and at three months it has almost covered up the midbrain (Fig. 128*C*, *M.B.*). At the time of birth (128*D*) it is relatively as large as later, although the brain has attained only about one-fourth its final weight. After birth the most striking changes in the brain take place in the cerebral hemispheres, and they are more modified with use than any other part. No small factor in

the evolution of the vertebrate forebrain is the fact that it is still plastic after the individual has come to lead a free existence—maturity is never attained in the sheltered seclusion of a cocoon. An important feature of the later development is the wrinkling of the walls of the vesicle as a result of localized growth (Fig. 128 *D*). The wrinkling begins in the olfactory region and then appears in the visual field (*V.A.*). Subsequently, the wrinkles, or "sulci," separating "gyri" (or "convolutions") involve only the cortex, and the pattern which they form becomes very complex. Certain of the gyri and sulci are definitely related to functionally distinct regions of the cortex, and these are fairly constant, but there is great variation in detail, and the pattern is as individual a matter as the aspect of the face.

Functions of the cerebrum.—What are the functions of the cerebral hemispheres? In fishes the olfactory apparatus associated with the hemispheres brings information to the animal from greater distances than the visual or other sensory apparatus possibly could, and it is of such profound importance in sharks that mere plugging the nostrils is sufficient to inhibit further feeding. As a result, the animal starves to death in the midst of plenty. Here the removal of the smell centers of the brain seems as serious as the removal of both cerebral hemispheres. In amphibians and reptiles the hemispheres are also concerned largely with smell and the correlation of this sense with taste and touch, which are also important in feeding. There is, however, always a part of the hemisphere which is not dominated by smell, and in mammals this non-olfactory part grows increasingly large, reaching its climax in man. The olfactory centers, on the other hand, are actually regressive in primates, but in most mammals they are still highly important. Even so highly developed a form as the dog, lives largely in a world of smell. His visual apparatus does not give him much clearer images than we have at twilight, and musical tones often seem to make him profoundly unhappy.

The higher mammals and even human beings can live for a time without cerebral hemispheres, and such decerebrate creatures

give us some insight into cerebral functions. They are extremely stupid, have no ability to profit by experience, nor do they appear to have any memories of past experiences. In a state of nature they would promptly succumb. It is significant, too, that they lack the initiative and curiosity which are characteristic of most vertebrates. Not infrequently the cerebral hemispheres have degenerated before birth in human infants. They may live for a week or more and during that time they exhibit the behavior of normal newborn babes. From this we may conclude that the cerebral hemispheres are not yet active at birth.

There is a case on record of a child that lived to be almost four years old although it was found after death (which was due to tuberculosis) that practically all of the forebrain had degenerated. It never did show any signs of intelligence but slept most of the time without moving. It reacted when strongly stimulated by light or sound, and, while it never showed signs of hunger, it refused everything except milk. The only evidences of emotions were those of discomfort or contentment. Such findings, together with the demonstration that the cerebral cortex in imbeciles and idiots is highly deficient, give us the clearest evidence that this part of the brain constitutes the mechanism behind the peculiarly human aspects of our behavior. It may here be said that anesthetics, such as alcohol and ether, after an initial phase of stimulation, depress the activities of the cerebral cortex long before any lower neural centers are affected. The human cortex is so highly susceptible that a slight reduction in its blood supply results immediately in a loss of consciousness—the ego vanishes completely. What does this mean? From the biologist's point of view it means that the functioning of the cerebral cortex is necessary for all of our higher conscious activities. It has the same relation to thinking that the bird's wings have to flying. The entire body is concerned in flying, but the wings are the specific organs of flight. So, too, most bodily activities have an effect on our mental processes, but the brain is the organ of the conscious activity. We do not know how the cerebral processes give rise to that consciousness

which we all know and call the "ego." Neither do we know exactly how a muscle contracts or a gland cell produces its peculiar secretion. Science is engaged in attacking these profound problems of life and has made more progress toward understanding them during a single century than the metaphysicians have made in twenty with their concepts of "vital spirits," a "mind" distinct from a "body," and the like.

Anyone who can comprehend the biological evidence for the interpretation of conscious activities as the outcome of physiological processes has a concept of the utmost practical importance. The normal functioning of the cerebral hemispheres is fundamental so far as behavior is concerned, for it involves a most significant element of control. All living is a marvelously unified series of processes: clear and accurate thinking and a striving toward ideals, as well as the normal performance of the other bodily activities, are vitally concerned in the guarding and developing of that supreme heritage of man—the power to think.

LOCALIZATION IN THE CEREBRAL CORTEX

In all mammals the cerebral cortex can be divided into fields or areas which differ from one another in structure, in synaptic connections, and in function. In addition to the olfactory area, we can always recognize such as are dominated by vision, hearing, etc. (Fig. 129). Herrick has likened them to the part of a telephone switchboard where outside wires are plugged in. They are, of course, vastly more complicated than this, but the analogy is illuminating. Two examples must suffice to illustrate the nature of these areas.

The visual area.—The lens of the eye throws an image on the retina, just as the lens of a camera projects one on the ground glass. The light activates certain types of cells in the retina and the impulses are carried by definite nerve fibers to definite parts of a primary visual brain center. Every part of the retina is represented by a corresponding region in the brain center, each part of which in turn sends axones to a definite part of the cerebral

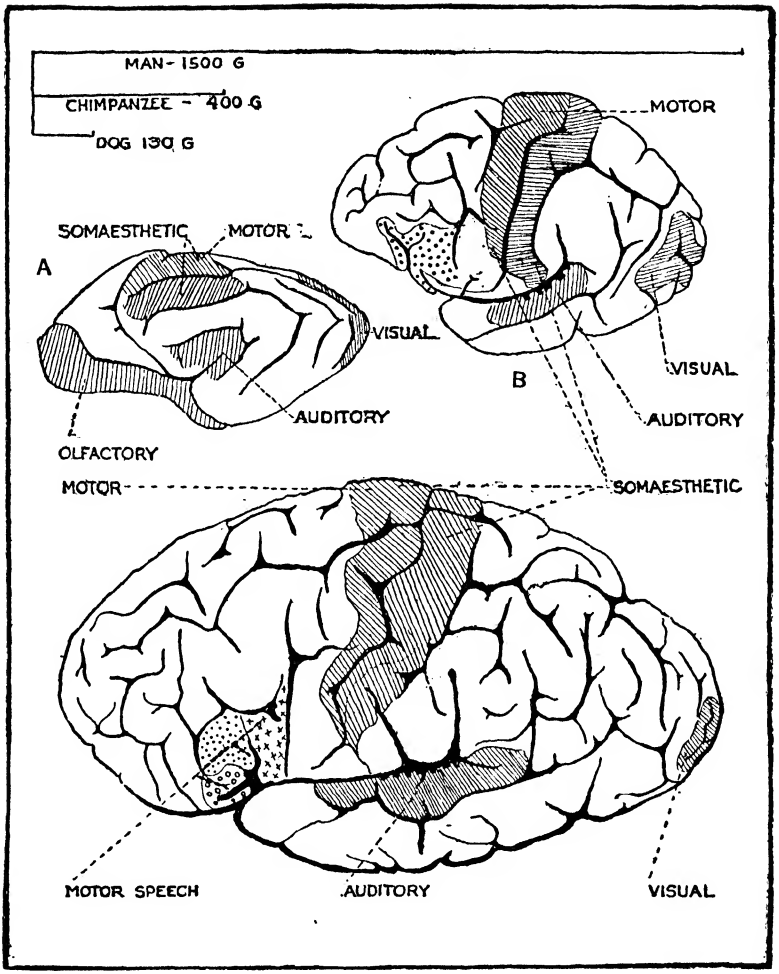


FIG. 129.—The left hemispheres of three mammalian brains drawn to scale to show the relative lengths. (Modified from Campbell, 1905.) A more accurate measure of the size relations of these three brains is given by the graphs at the top which indicate the relative weights of entire brains weighed fresh. *A*, the brain of a large adult dog. *B*, the brain of a young adult chimpanzee. *C*, from a human brain somewhat below the average size.

The position of certain primary sensory centers is indicated. In the primate brain the small olfactory centers do not show in this view (but see Fig. 128, Olf.). The greater part of the visual area is on the inner side of the hemisphere so that it does not appear here but it is well shown in Figure 128, *D*. The region which corresponds to the human motor speech area (chap. xvii) in the chimpanzee is indicated by large dots. It is quite uniform in structure as compared to the structurally complex motor speech area of man.

cortex. The retinal image is projected, as it were, to the cortex, and as a result of the activities there we become conscious that we have seen something. This is not the "mind's eye," but vastly simpler, for this region of the cortex may be intact and yet the individual may not recognize the object which he sees. It represents only the beginning of such a process of recognition, and is a necessary link in the chain of associations involved in comprehending what we have seen. Much of the evidence for these conclusions comes from the conscious experiences of human beings who have suffered localized injuries to the cerebral cortex, but the anatomy of the system has been worked out in various other mammals in great detail. The visual area is always located at the hinder end of the hemisphere (Fig. 129), and in the primate brain little of it appears in the lateral view which is presented in the figure (but see Fig. 128*D*, *V.A*).

The somesthetic area.—Impulses from the muscles, joints, etc., which are involved in our judgments of the weight, the shape, and texture of objects as well as the position of our limbs in space when blindfolded—all of these reach a definite cortical field. Closely associated with it is the primary cortical center for touch and the two are grouped together as the general sensitivity, or somesthetic area (Fig. 129). The forward end of the somesthetic area has established a direct connection with the lower nervous centers which directly control the voluntary muscles. Because of this, and since it is easily excited to activity by experimental means, it has been called the "motor" area. Its histological structure is so peculiar that it can be recognized at a glance in preparations from any mammalian brain.

These and the other sensory centers are features common to all mammals. They always have the same relative position in the hemisphere. It is clear from Figure 129 that in the ape the conditions are very like those found in man, particularly in regard to the primary sensory centers. Wherein, then, does the human cerebral hemisphere differ? An outstanding difference is size. Some figures will emphasize the progress in growth alone that has

been made during human evolution. At birth the human brain weighs about 400 grams and at maturity it usually varies from 1,100 to 1,550 grams, but it may reach more than 2,000 grams. It averages about one-fortieth of the body weight. The brain of an adult chimpanzee may reach 400 grams and in the gorilla it may weigh somewhat more. The brain of a 400-pound gorilla is no larger than that of a newborn babe and represents about one three-hundredth of the body weight!

Association centers.—More significant than mere size is the fact that the greatest growth is in those regions of the human cerebral cortex which are structurally and functionally the most complex. The regions to which we refer lie between the primary sensory centers and are occupied by the association centers. They are present in all mammalian brains, but they must be dismissed here with a few words, as they are discussed in a subsequent chapter. A study of Figure 129 will show that in the human brain there are not only more convolutions in the region between the primary sensory areas but that the pattern is more complex than in the brain of dog or chimpanzee. More than this, the structure of the individual areas is more complex, as is illustrated by the one association area which is mapped in the figure (motor speech area). The ape's brain not only lacks the characteristic differentiation in the corresponding region (which is indicated by stippling), but all the cortex in front of the motor area is relatively feebly developed. This end of the brain is pointed, and correlated with it is the low retreating forehead. In this frontal region of man there are many centers comparable to the motor speech area in that they are farther removed from the direct influence of any sensory system and have widespread and complex associational connections. In the last analysis, then, the most striking difference between man and brute is in the development of association centers. These are to be regarded rather as anatomical regions than as functional units, because it is highly improbable that any one of them acts by itself. As we understand it at present, a word or an idea comes into consciousness as a result of innumerable

cortical reverberations back and forth from one cell or group of cells to another. The mathematically possible number of permutations and combinations among cortical cells is enormous and the known complexity of their associations is perfectly adequate to explain any form of intellectual activity. (Herrick, ***Brains of Rats and Men***, chap. i.)

The correlation of one cortical cell with another seems, like other nervous activity, to involve changes in the nerve cells which give us a material basis for learning and memory. The ability to modify the nervous pathways, i.e., to fix an experience in the mind, the power to remember and to associate memories, varies greatly in different species and individuals. So, too, the period during which the cortex is capable of modification (learning) varies in length. At the age of two years a dog's ability to learn is rapidly decreasing. The chimpanzee has passed the zenith of his mental plasticity before the human being has reached puberty. There are many human beings who show little evidence of intellectual progress after this stage, but in most human strains there are individuals whose cortex remains plastic for two score years or more. This gradual lengthening of the period of modifiability has assuredly played a major rôle in making man what he is today.

History has recorded a few men who have had a stupendous capacity for remembering and associating and recombining experiences. They are the supreme geniuses like Aristotle, Leonardo da Vinci, Shakespeare, Goethe, and Helmholtz. To such as these we owe much of our progress as a race. With the spoken and written word at their command, they have eliminated time, and their influence will be felt for centuries to come. When we compare their intellectual achievements with those of the average citizen it seems impossible that the latter can be making the most of his innate powers.

In what direction may we look for progress? There is no evidence that the upper level of intellectual attainment has risen during historic time or that the race is likely to produce a higher percentage of geniuses in the future. Our most obvious need is in

the improvement of the social relations among men. Some suggestions toward this end are made in chapters xiv and xvii. It may be added that those individuals who do more than merely acquire information, who are capable of true education, are lifted thereby above the level of inherited reflex to the heights of intellectual control. Their number can assuredly be increased as time goes on, and mankind will profit accordingly. The greatest progress, however, will probably come through the labors of the sporadic genius, the pathfinder and torchbearer who must be recognized promptly, liberated from the bondage of class and caste and disease, and left free to develop his capacities and attain his ideals. Our greatest hope lies in him.

SELECTED REFERENCES

1. C. J. Herrick, *Introduction to Neurology* (3d ed., W. B. Saunders & Co., Philadelphia, 1922).

2. C. J. Herrick, *Brains of Rats and Men* (University of Chicago Press, 1926).

3. G. H. Parker, *The Elementary Nervous System* (J. B. Lippincott Co., Philadelphia, 1919).

CHAPTER XVI

THE DYNAMICS OF LIVING PROCESSES

ANTON J. CARLSON

CONTENT AND METHODS OF PHYSIOLOGY

Physiology endeavors to analyze the dynamics of living matter, that is, the processes or changes that go on in living organisms rather than the structures that remain after death. The latter may be studied by chemical and physical methods in the dead animal. General physiology is concerned principally with investigation of the processes that are common to all living cells. Chemical physiology, or physiological chemistry, deals with the chemical composition of living matter and endeavors to analyze living processes by the tools of chemistry. Physical physiology is concerned with organ functions and correlation of organs, using the tools of physics as well as of chemistry in the investigation. Psychological physiology deals particularly with the nervous system, so far as this can be analyzed by the methods of controlled animal behavior and by means of introspection. Pathological physiology, or experimental pathology, investigates and classifies the changes in living processes induced by disease. These divisions of physiology overlap. Practically all known living processes involve both chemical and physical factors. The science of physiology depends on, and makes use of, the data and many of the methods of chemistry, physics, zoölogy, anatomy, and pathology. To be sure, physiology has also to devise and use methods peculiarly its own. Many substances of profound importance in living processes (e.g., the vitamins, the enzymes, the hormones, etc.) have, so far, defied chemical analysis, and the action of many of these substances cannot at present be stated in terms of complete chemical or physical reactions. In such cases our analyses and data depend on, and are expressed in terms of, the so-called biological tests.

But no student goes very far in physiology before he becomes profoundly impressed by the interdependence and essential unity of all sciences.

1. **Chemical analysis.**—This method gives us our main information respecting the composition of cells and organs. But such analysis is not necessarily accurate in regard to the complex relations of the various substances in the living system, since the analysis itself practically always kills the living system. It would be difficult and scientifically precarious to reconstruct a watch on the basis of the débris remaining after it had been ground up in a mortar, even if a few wheels were only partly fragmented. Our difficulties are correspondingly great, and the results often equally uncertain, when we attempt to reassemble the products of chemical analysis of dead cells into living organisms.

However, the methods of chemistry have yielded nearly all of our present knowledge of the composition of the digestive fluids (saliva, gastric juice, intestinal juice, pancreatic juice, bile), the urine, and the blood plasma in health and in disease. These fluids are products of cells or organs, and chemical analysis of these fluids gives us more direct and unequivocal information than does chemical analysis of living tissues after their death. Nevertheless, the methods of chemistry reveal the approximate nature of many processes in living cells, such as the utilization of sugar by the contracting muscle, the exhaustion of the liver glycogen by neuro-muscular work and by external cold. The tools of chemistry have similarly brought out most of our present information about the composition of the foods, the changes induced in the foods in digestion, and the story of the foods in the tissues during the processes of growth, repair, and other forms of energy changes.

2. **Physical methods.**—The study of living organisms by methods and principles developed in the science of physics has yielded striking results, particularly in the field of energetics of the animal machine. When Lavoisier demonstrated, with the relatively crude instruments then available, that the utilization of food for energy by the animal body is essentially oxidation, and

that the oxidation of food in the body yields practically the same quantity of energy in the form of heat and work as does the combustion of the same food in a calorimeter, the essential nature of respiration was for the first time made clear, and the vague but convenient "animal" and "vital spirits" evaporated, at least from this field of physiology. To be sure, there is more to foods than the energy aspect; that is, the value of foods cannot be entirely expressed in calories, as, for example, the inorganic salts, the vitamines, and the proteins. Nevertheless, the great body of data yielded by persistent research during the last one hundred and twenty-five years in the fields of animal calorimetry and of the Basal Metabolic Rate, constitute an important element in the mechanistic conception of the life-processes.

Man, ~~and many other animals~~, have special receptors, or mechanisms, that are stimulated by light, sound, heat, gravity, movements dependent on inertia, and probably molecular motion. These are the eyes and the ears (sound, the cochlea; gravity, the vestibular sacs; inertia, the semicircular canals); the olfactory epithelium in the nose (molecular motion); and the temperature sense organs in the skin (heat and cold). The stimulations of these specific senses by each specific type of energy form the initial links in some of the most important adjustments of the organism to environment. To say that the physiologist who investigates the mechanics of these senses must in the first place draw on the latest and most authentic information that the science of physics offers on the nature of light, sound, heat, gravity, and inertia is merely stating the obvious. In recent years physiologists have discovered other important actions of radiant energy (violet end of spectrum) on the growth and life of bone, on blood composition, and in prevention of disease (rickets). The X-ray has been developed into a most useful means for accurate investigation of living processes both in health and in disease.

In the fields of electricity, osmosis, and surface-tension phenomena, physiology has also borrowed from physics both facts and methods of importance in the analysis of life. Electrical phe-

nomena seem to appear in practically all physiological processes (muscle contraction, gland secretion, all degrees of complexity of nervous action), and electricity as an artificial stimulus has been most useful in the analysis of the nature of irritability of living matter. Osmotic equilibrium in body cells and body fluids under the ceaseless changes of life is a factor of basic importance, as is shown in the diseases that are induced by a disturbance of this equilibrium. Recent physiological investigations also indicate that surface tension, and electrical polarization of cell surfaces and intracellular membranes play important rôles in many physiological processes.

3. The service of the sciences of zoölogy, embryology, and normal and morbid anatomy to physiology, consists essentially in furnishing clear information on organogenesis and gross and microscopical structure of the adult organs in health and in disease. Anatomy shows the kinds of tissues that go to make the particular organ complexes, and the orientation of these tissues in the organ. Comparative anatomy reveals also the interesting fact of identical functions being carried out by quite different mechanisms. For example, the frog gets air into its lungs by positive pressure (swallowing) and exhales the air in part by active contractions of the lungs; while the bird and the mammal suck air into the lungs by expanding the chest cavity through muscular action; the normal expiration is entirely passive, and in both acts the lungs behave as a passive elastic sac.

4. Some specific biological methods of analysis.—(*a*) *Organ isolation.*—The physiologist takes the living animal as he finds it today. In previous chapters you have seen how this animal varies in complexity from the one-celled *Amoeba* to the billion-celled man. In the multicellular and multi-organed animal, such as man, the method of organ isolation has been an important path of progress in physiology. The method in its simplest form is the removal of one organ from the rest of the body so as to determine what particular things this organ can do by itself. Thus it has been shown that the excised muscle and the excised nerve live

for a long time outside the body, and such studies have yielded invaluable data on the nature of muscle contraction, nervous irritability, and nervous conduction. The heart, even of man, beats for hours outside his body, provided the oxygen supply and the temperature are right. Such experiments show that the cause of the heart beat is different from that of the contraction of the leg or the arm muscles, and that not even the blood is immediately necessary for the heart beat; in other words, that the periodic contraction of this important organ is due to some specific properties of the heart tissues. In fact, the heart tissues can be grown in nutritive media (tissue culture) outside the body for years, and heart tissues so grown may continue to show rhythmical contractions. The alimentary canal and the uterus will execute practically normal movements outside the body. Less success has so far been attained by this simple method when applied to the glands and the different parts of the central nervous system.

Organs may be left *in situ*, but separated from their nervous connections. Such experiments show that, after cutting out a section of their respective nerves, the skeletal muscles and the salivary glands gradually disappear, while such organs as the kidneys, the alimentary tract, the liver, etc., continue to do their work practically in a normal fashion. In other words, the nervous connections are essential for the life and work of the first group, but not of the second.

An application of the method of organ isolation of even greater importance is that of removal of a particular organ from the animal, followed by careful study of subsequent deviations from the normal physiological processes of the animal. This method is applicable to many organs, such as the endocrine glands (e.g., thyroid), different parts of the brain, and the spinal cord, the digestive glands, the gut, etc. The method is not applicable to the red bone marrow or the lymph glands, because these organs are so widely distributed in the body that complete surgical extirpation is impossible. It need scarcely be pointed out that removal of a more or less important organ will produce effects

identical with destruction of this organ by disease processes, and the method has been of inestimable service in the discovery of the cause (and in some cases, control) of such diseases as diabetes, cretinism, myxedema, tetany, aphasia, and other disorders.

b) *Biological tests.*—When we are dealing with substances of unknown compositions, such as the vitamins, the digestive and the intracellular enzymes, and, at present, most of the hormones, we may still determine where these substances are formed, in what concentration they are present, the kind of influence they exert on the body as a whole, or on particular organs, the duration of such action, etc. Such data are frequently of great importance both in physiology and in medicine, although they cannot at present be expressed in final chemical and physical terms. A great deal of our physiological knowledge is, at present, of this type. These data are, nevertheless, quantitative, within the limits of the methods, and constitute necessary steps in the direction of an ultimate physico-chemical analysis of life. The sensitiveness of some of these biological tests is striking. A few milligrams of a vitamin of unknown composition makes the difference between health and serious disease or death. The uterus responds (with contraction) to pituitrin (a substance found in a gland at the base of the brain) in a dilution of 1/100,000,000. In fact, living cells or complex animals appear in some cases to be the most sensitive "chemical indicators" known.

HUMAN VERSUS ANIMAL PHYSIOLOGY

The reader who has carefully studied the previous chapters on various aspects of biology will not be surprised when told that there is very little physiology that is specifically human. Man breathes the same air, eats the same foods, voids essentially the same waste products, and behaves essentially the same as other animals. The students of zoölogy and of anatomy are impressed by the essential identity in the structural plan of all animals, from fish to man. The student of physiology is, if possible, even more profoundly impressed by the essential identity in the chemical

and physical mechanism of internal and external correlation. The dynamics of the digestive, the circulatory, the respiratory, the endocrine, and the neuro-muscular systems are essentially identical from fish to man, and in the dynamics of most of these systems there is very little evidence of progressive evolution. They seem to have been stabilized early. In the portion of the nervous system called the brain, progressive evolution in the sense of increase in number of cell units and in the complexity of their interrelations is clearly in evidence (see chapters xv and xvii). The possession of this greater quantity of brain material parallels the greater complexity of some human reactions. One seems forced to the conclusion that the second is dependent on the first, a conclusion supported by a mass of valid evidence from the field of organic nervous disorders in man and from brain injury experiments on animals.

Man has more cells and cell connections in his brain than has any other animal. So far as we know, man has no new kinds of brain cells or brain cell connections. On the anatomical and biochemical side, so far as present data go, the difference in brain between man and other animals is a quantitative difference. Cerebral association areas are present on the cortex of all higher animals; in man these areas are larger, and therefore better. On the physiological side, the brain of man depends upon the same kinds of nervous impulses as in the case of other animals. Man has in common with other mammals inherited reflex mechanisms serving internal and external adjustments. We find memory and capacity to learn, and the seeming rudiments of inference or reasoning at least in the higher mammals; but man, on the whole, learns quicker, seemingly retains in memory a greater variety of past experiences, and makes greater use of this memory material. When we survey man's present achievements in science, in the arts (including oratory), in political and social institutions, and note at the same time the apparent paucity of such behavior in other animals, one is tempted to conclude that in these capacities, at least, man has a qualitative superiority over other mammals; here, at last,

we have something new under the sun! Indeed, the brain capacities rendering these achievements possible seem so great that they challenge the theory of a purely quantitative brain superiority of man as an adequate explanation.

But let us put the problem in a different way. In our admiration and awe before the magnificence and the beauty of the Pyramids, the Parthenon, the cathedral at Cologne, or the Tribune Tower we are likely to forget the crude dwellings of primitive man and the thousand stages between this and the modern triumph of architectural engineering. This is, after all, a quantitative development, for which merely larger cerebral association areas may be an adequate basis. One may possibly trace a similar quantitative progress in complexity between the first log used as a bridge across a stream and the modern marvels of bridge building, between the twitching frog legs observed by Galvani and the wireless telegraphy of today. We may seriously raise the question whether the first man or animal who placed the log across the stream for a bridge was not a greater inventor than the modern builder. He was, if he invented the idea of a bridge.

The other Primates have hands not so different from the human. They have essentially the same motor control of the hands as man, but so far their use of the brain-hand mechanism for mechanical invention is meager. All mammals have a voice box at the top of the trachea, and such cerebral motor control of the muscles in this voice box, and motor control of respiration, tongue, and lips, as apparently might serve for articulate speech. In the higher mammals the third frontal convolution (speech area) is present in the brain. All mammals, apparently, have the hearing mechanism necessary for the initiation and control of speech. In view of these facts, the paucity of evidence of articulate speech in animals other than man seems at present a riddle. But the physiologist does not accept the great development of articulate speech in man as something qualitatively new; he must first have more reliable information on the amount, mechanism, and physiological significance of vocalization in the rest of the mammals. We

cheerfully admit that the gaps in our knowledge of the biochemistry and the biophysics of the nervous system are large enough to shelter an additional "building stone" in the proteins of the human brain, an additional lipoid, phosphatid, or potassium ion. We admit, further, that such changes may be the mechanisms for qualitatively new physiological processes. But science does not progress by such assumptions, for all the known facts, so far as they can be stated in known mechanisms, appear to be adequately explained on the basis of more brain cells and synapses. To the physiologist the thing that seems new in man's capacity or achievement is not the actual progress in the arts, in institutional organization, or even in science, but the urge to new achievements that appears from time to time in some men. But even this urge, called by poets the divine curiosity, by the guardians of the existing order, a diabolical restlessness, is probably specifically human only in its degree.

"VIVISECTION"

Physiology is primarily experimental. Since most, if not all, of the essential physiological processes in man are qualitatively identical with those of other animals, and since activities can be studied in "going concerns" only, it follows that physiological study and investigation can be done only on the living cell, the living organ, the living animal, the living man. Hence the progress of our knowledge of the bodily functions in health and in disease depends very largely upon the experimental use of animals. This brings up the question of "vivisection." As defined by opponents of the sciences of physiology and medicine, "vivisection" is the cruel and useless mutilation and killing of animals in experiments without adding to our knowledge, or helping us in the control or eradication of disease. Some groups that have rallied to the support of the "anti-vivisection" propaganda deny the material existence of disease. No facts or arguments of science can reach these people. Some anti-vivisectionists deny, on ethical grounds, man's right to use other animals for any purpose whatever that furthers his own ends. But organic life is not run on

those principles. Most of us take steps to get rid of animals harmful to us, and cultivate animals useful to us. In some states "anti-vivisection" has become an issue in state elections and in state legislatures. Now, what are the facts about "vivisection?"

1. In experiments on animals that may cause suffering, the same anesthetics are used as in human surgery. These anesthetics abolish pain and consciousness. Many physiological functions are so upset or altered by intense pain that they cannot be studied in the suffering animal. Pain must, therefore, not enter into the experiments. The experimental use of animals in physiology and medicine, as practiced by competent investigators in properly equipped and responsible institutions, is not cruel or wanton.

2. In answer to the charge that "vivisection" is futile even when done by responsible investigators, it may be answered that the greater part of our present knowledge of the nature of normal and pathological body processes has been gained through experiments on animals and voluntary experiments on man. Any addition to knowledge is, in itself, worth its cost. But if we define value in the common or utilitarian sense we may point to the advances in the control or eradication of such diseases as diabetes, rickets, diphtheria, goiter, etc., in which animal experiments have formed necessary links. Biological science, scientific medicine, public health, and hygiene would be tragically retarded by taking the tool of vivisection from the hand of the investigator.

3. In view of the foregoing facts, how can we account for, and how are we to meet, the "anti-vivisection" propaganda? In the first place, almost any "cause," no matter how false, absurd, or impracticable it may seem to most sane people, finds some advocates. This may be a part of nature's "trial and error" in the ponderous experiment of organic evolution. Secondly, the leadership in the "anti-vivisection" propaganda is usually taken by paid propagandists. But the majority of the so-called anti-vivisectionists are ordinarily normal, honest, and kindly people, who do not know the facts at issue and are swayed by the false assertions that "vivisection" is cruel, inhuman, and useless. If these

people knew the true facts they would be our friends and supporters.

SOME EXAMPLES OF PHYSIOLOGICAL CORRELATION

In unicellular organisms co-ordination of the internal physiological processes is purely or primarily humoral; in the higher animals having differentiated organs and nervous tissues, it is partly humoral, partly nervous. These two mechanisms of correlation are also involved in the adjustment of the organism to the external environment, the nervous mechanism playing here the predominant rôle. By humoral control of physiological processes we mean the initiation, augmentation, or inhibition of living processes by chemical substances carried to the cells and organs by the blood and lymph, or distributed by diffusion through the solid tissues. This is sometimes called chemical co-ordination, or chemical control. The latter term is less desirable because it appears to imply that nervous co-ordination is not chemical, while, as a matter of fact, our best evidence today is to the effect that the nervous impulse is primarily chemical, or rather a physico-chemical process.

REFLEX ACTION

When light enters the eye, the pupil contracts. When a person passes from a well lighted into a poorly lighted room, the pupil dilates. In man and the other mammals this is a reflex action, the mechanism being fixed by heredity and in most animals ready to function at birth. The light rays acting on the retina start nervous impulses that pass up the optic nerve to the midbrain where they connect with nerve cells that send motor fibers out by another nerve to the circular musculature of the pupil. The impulses in the optic nerve activate the latter nerve cells in the midbrain, and when the nervous impulses from the brain reach the circular musculature in the pupil, this musculature contracts and the pupil becomes smaller. We are not now concerned with the utility or advantage of this reflex. The reflex is not dependent on the cerebrum, or on consciousness. It is present in the anesthetized

person, and it persists after removal of the cerebrum. We are conscious of the light or darkness, we are not conscious of the narrowing or widening of the pupil. The reflex is abolished by cutting the optic nerve, by destroying the motor nerve cells in the midbrain, or by cutting the motor nerve fibers that pass from the midbrain to the muscle surrounding the pupil, because either of these injuries interrupts the nervous path of the reflex.

When any irritant (good or bad tasting foods, acids, dry substances, etc.) is put in the mouth, there is an increased flow of saliva from the salivary glands. Substances in the mouth do not come in direct contact with the salivary glands, as these are located at some distance from the mouth cavity. The substances in the mouth are not absorbed and carried to the salivary glands by the blood; hence we are not dealing here with a humoral or simple chemical correlation. This is what happens: The substances in the mouth stimulate sensory nerve endings in the lining of the mouth cavity; the impulses in these nerves connect with and stimulate the nerve cells in the brain that sends fibers out to the cells of the salivary glands. These nervous impulses acting on the gland cells initiate or augment the production of saliva. This is a familiar example of a secretory reflex, whose essential mechanism is also fixed by heredity. It is not dependent on the cerebrum or consciousness, although it can be modified by the experience of the individual and by various cerebral processes.

When the sensory nerves distributed in the abdominal organs are strongly stimulated, as by a "solar plexus blow," the heart slows down, or stops completely for a short time, and the individual may faint. This is not due to any direct or mechanical injury to the heart. It is a complex reflex, involving the following chain of processes: impulses over the visceral sensory nerve fibers enter the spinal cord and by isolated conduction paths in the cord reach the medulla (hind brain), where they connect with and stimulate nerve cells that send their processes down the vagi nerves to the heart, and these vagi nerve impulses slow the heart, or, if strong enough, stop the heart temporarily. When the heart

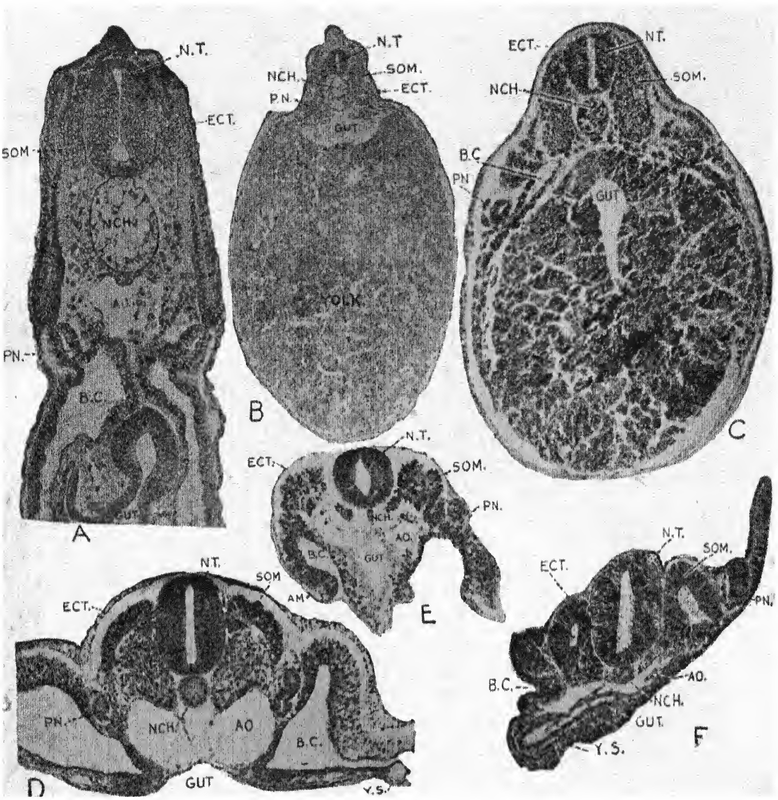


FIG. 127.—Photomicrographs of thin slices cut across the bodies of several vertebrate embryos to illustrate the fundamental plan of structure. The same parts are present in each case but differ in relative size or in degree of development.

A, from a shark embryo (*Squalus*) about 7 mm. long in the same stage as that shown in Fig. 125, *A*. ×55 diameters. (From the Embryological Collection of F. R. Lillie.) *B*, from a tailed amphibian (*Necturus*) in the same stage as that shown in Fig. 125, *B*. ×13. (From the same collection.) *C*, from a tailed amphibian (*Amblystoma*) 5 mm. in length. ×43. *B* and *C* show the relations of embryo and yolk. In *C* the yolk is all included in the cells of the wall of the primitive gut which is very thick. In *B* the embryo rests on a much larger mass of yolk. In *C*, *D*, and *E* the yolk sac is relatively very much larger and could not be included in the photographs. The general relations appear in Fig. 126, *A* and the relations of embryo to yolk sac in man are shown in Fig. 124, *D*. *D*, from a chick incubated for 2 days and magnified 85 diameters. *E*, from a rat $10\frac{1}{2}$ days after fertilization. ×85. *F*, from a human embryo (H951) about $3\frac{1}{2}$ weeks old from the Embryological Collection of the Department of Anatomy. ×85.

Am., Amnion; Ao., aorta; B.C., body cavity; Ect., ectoderm; Gut, cavity of gut; N.T., neural tube; Nch., notochord; Pn., primitive kidney; Som., somite; Y.S., yolk sac.

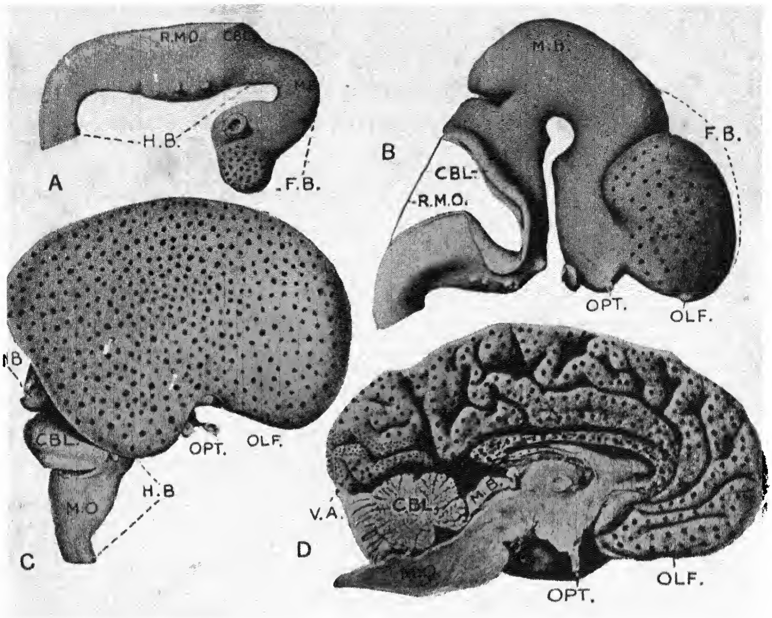


FIG. 128.—Stages in the development of the human brain to illustrate the spread of the cerebral hemispheres which are indicated by the coarse stipple. *A*, *B*, and *C* are views of the right side somewhat modified from Hochstetter (1919, Figs. 12, 35, and 47). *D* presents the medial surface of the right side of a brain cut longitudinally in the midline. (From Retzius, 1896.)

A, drawn from a reconstruction of the brain of a human embryo 7.5 mm. long and about 5 weeks old. $\times 5.7$ diameters. The cerebral hemisphere here is dorsal and terminal in position, as will be readily appreciated if the reader will imagine the sharp bend at M.B. as straightened out. *B*, drawing similar to the foregoing from a 19.4 mm. embryo about 7 weeks old. $\times 2.6$. A photograph of an external view of a slightly younger embryo is shown in Fig. 125, *F*. *C*, drawing of the brain of a 68 mm. embryo about 12 weeks old. $\times 3$. *D*, from a photograph of a new born babe's brain, 0.6 life-size. The area mapped out by the closer stippling is the visual area referred to below.

Cbl., cerebellum; F.B., forebrain; H.B., hindbrain; M.B., midbrain; M.O., medulla oblongata; R.M.O., thin membrane which forms the roof of the medulla oblongata; Opt., optic nerve; Olf., primary center for smell; V.A., visual area (see p. 465).

is markedly slowed up or stopped the blood pressure falls, the brain becomes temporarily anemic, and unconsciousness or fainting follows because of the temporary asphyxia. This is an example of reflex inhibition.

When the sensory nerve endings in the skin are stimulated in various ways, reflex actions are initiated, involving various types of movements of the legs and the trunk. Many of these reflexes take place through the spinal cord and do not involve cerebral processes or consciousness, as is shown by the fact that complicated reflex movements, such as stepping or walking, can be induced by such stimuli in the hind legs of a dog with the spinal cord sectioned in the chest region. The same phenomenon has been observed in man after injuries to the back, severing the spinal cord. By rubbing the skin of the back the complex "scratch reflex" can be induced in a sleeping dog or in a dog with his cerebrum removed.

A bird with its cerebrum removed walks and flies apparently as perfectly as a normal bird. A frog with its cerebrum removed swims and leaps. From observations on man it is highly probable that most, if not all, conscious processes are absent when the cerebrum has been removed. And yet, the decerebrated pigeon and the decerebrated frog, when induced to walk, leap, or swim, avoid obstacles in their paths, thus showing unconscious guidance of these reflex processes by visual impulses. When the stimuli acting on the skin are strong or destructive enough to cause some degree of pain in an intact animal, the usual reflex response is such as to carry the limb or the body away from the stimulus, or to remove the stimulus from the skin. Thus, pinching the toes causes flexion, or retraction, of the legs in the spinal (decerebrated) frog, the spinal dog, and the spinal man. If a drop of vinegar is put on the skin of the back in the spinal frog, the hind legs are in a series of reflex motions bringing the foot in contact with the spot of the skin irritated by the vinegar in a series of brushing movements. If a decapitated turtle is severed in the middle, leaving in the posterior half the hind legs, the tail, and

the portion of the backbone containing the posterior end of the spinal cord, the following remarkable events occur on pinching the tail: the hind legs are extended backwards in a series of movements powerfully pushing against the fingers or instruments pinching the tail. These are examples of relatively simple and of exceedingly complex reflex actions induced by stimulation of sensory nerves in the skin and involving limb movements or locomotion. But these responses are not the only effects of skin stimulations. They produce at the same time a multiplicity of motor or inhibitory nervous discharges from the spinal cord and medulla into the heart, the blood vessel walls, the stomach and intestines, the urinary bladder, and, when the cerebrum is present action on conscious processes.

Most reflexes seem useful. They adjust the external motor mechanism to the changes in the environment. As long as everything is normal they initiate, augment, or retard internal processes in adjustment to the work at hand. To be sure, there are a few reflexes that at present seem useless (like blushing), or actually detrimental (like inhibition of the heart from pain, or dilation of the stomach in anger). But most of the reflex actions adjust the organism so admirably to changes in the external and the internal environment, and to continuous and occasional needs of the organism, that the reflexes have been described as purposive, and this apparent purposiveness has been used in teleological interpretations of life as evidence of design in nature. From the point of view of organic evolution, seriously discordant reflexes would so jeopardize the individual's chances of living that he would leave no descendants to perpetuate the incongruity, while a few indifferent or less seriously harmful reflexes would not lead to speedy extinction. We see this happen every day in the field of disease in man and animals. Disease is upset of normal functions, that is, normal chemical and reflex co-ordination. Less serious inco-ordination weakens the individual; more serious inco-ordination kills him. In brief, reflex actions are essentially fitting and seemingly purposive, not because of design, but because the seri-

ously unfit perish. The philosopher may challenge this interpretation on the basis of some of the reflexes associated with pain and the depressant emotions. We have fair objective evidence of the existence of pain mechanisms far down in the animal scale. Mechanisms producing the cerebral states of depressant emotions (fear, anger, nostalgia, hate, melancholia) seem to be present in all mammals, and some of them even in all vertebrates. It is a curious fact that prolonged and intense activity of these mechanisms may greatly upset the normal physiological processes, and may thus jeopardize life itself, especially if any essential function is already weakened by disease or overstrain. Thus the pain produced by the aspirating needle rubbing the lining of the chest cavity (as in removing the fluid in the chest in persons with pleurisy) may kill the person by reflex inhibition of the heart. We have some creditable investigations on the physiology and the psychology of pain and the depressant emotions. There is also a plethora of useless, albeit harmless, verbiage on the subject. Space permits only a mere allusion to the problem. It is true that pain, fear, anger, etc., at least in animals below man, are potent forces for action. But it may be that the mechanisms for chronic depressant emotions, for the sustained "hymns of hate," are evolutionary bypaths that will eventually destroy the animals harboring them unless there should come about a parallel change removing important bodily processes from their influences.

The simple reflexes do not vary in a qualitative sense and are, therefore, predictable. As the reflexes increase in complexity they become more variable and less predictable. This is particularly true where reflex mechanisms are altered by individual experience. The animal being normal, we can always be sure that the pupil will contract when strong light falls on the retina. On the other hand, we cannot predict, for example, the course of action a dog will take in response to a reflection of light that mirrors the image of a man on the dog's retina, unless we know with a certainty the dog's previous experience with that man, and unless we know the dog's heredity and total training, as well as his major

cerebral processes at the moment. If past associations of the dog and the man have made them friends, the dog may approach the man; if enemies, the dog may either run away or prepare to fight the man, depending on heredity and total experience with the genus Homo. If the man is a stranger, the dog may pay no attention, or start to investigate, or start to fight, the behavior being determined by the variables of heredity and past experience. The man may be stranger, friend, or foe, and still the dog may do none of the things predicted, because of more potent reflex processes of the moment. If in rut, the dog will cling to its mate and ignore the man, in either rôle; if the image of a rabbit falls on the dog's retina side by side with that of the man, the dog may or may not pursue the rabbit rather than react to the visual impression of the man, depending on whether or not the dog has previously been trained to leave all rabbits severely alone.

CONTINUOUS AND DISCONTINUOUS REFLEXES

The reflexes we have considered so far may be called occasional, or discontinuous, that is, the stimuli leading to the reactions are present or absent, depending on fortuitous circumstances, and when they are absent the reflex mechanism is at rest as regards the particular type of response induced by the stimuli. There is also a large and important group of reflexes that may be called continuous. In fact, we may divide all nervous processes into discontinuous and continuous. The latter group establishes some of the necessary working conditions for the discontinuous reactions. The discontinuous reflexes are more apparent, and hence are usually given greater attention by people not versed in physiology.

MUSCLE TONUS

The term tonus, or tone, designates a certain but variable degree of continuous activity in any tissue, such as a certain degree of excitability in nerve cells and reflex nerve centers, or a certain degree of continuous contractions in muscle. Our information as to detailed mechanisms of tonus is most extensive in case of the muscle and the nervous tissues. During life, and as long as the

nervous connections between the muscle and the central nervous system are intact, the muscle is never completely relaxed—it is in a state of continuous but variable contraction. The occasional contractions leading to motion and locomotion are superimposed on this tonus. In the case of the skeletal muscle the tonus state does not give rise to movements, though extreme tonus produces rigidity; but in the visceral musculature variations in tonus change the sizes of the hollow organs. Muscle tonus decreases during sleep, when a person lies down, and when by other means reflex and conscious cerebral processes are reduced to a minimum. When the central nervous system is destroyed, or the nerves to the muscle are severed, tonus disappears completely and the skeletal muscle dies, as we see after nerve injuries or in infantile paralysis. It has been shown that all normal muscle tone is a reflex phenomenon, depending on sensory nerve impulses (in most cases unconscious), stimulating the cells in the spinal cord and brain that send the motor nerve fibers to the muscles. If the reflex chain is broken at any point, the tonus fails. Sensory nerves in muscles, tendons, and joints are important parts of the muscle tonus reflex. But it may be said that every sensory nerve in the body acts on the tonus mechanism via the reflex centers in the spinal cord and the brain. The tonus of the smooth musculature of the gut, the blood vessels, etc., is less dependent on nervous reflexes through the central nervous system. This musculature does not die on being severed from its brain and cord connections. The tonus fails at first, but after weeks or months some tonus returns. This musculature, being less differentiated than the skeletal musculature, seems capable of reverting to a tonus initiated and controlled by simple chemical regulators.

In some of the internal organs the tonus reflex into the musculature is one of inhibition, not contraction. When the vagi nerves are severed, the lower end of the esophagus in mammals, and the entire esophagus in turtles, goes into a prolonged spasm, showing that these nerves normally keep this part of the gut more or less relaxed. When the vagi nerves are severed in the frog, the muscle

in the frog's lung goes into extreme spasms lasting for months; when the vagi are severed in mammals, the heart beats faster, showing that continuous impulses down these nerves keep the lung muscles relaxed, and slow the heart.

TONUS IN THE SPINAL CORD AND THE BRAIN

For the co-ordination and execution of the occasional reflex process in the central nervous system, the irritability of the nerve centers must be maintained at a certain level by a constant stream of impulses over the sensory nerves (proprioceptive system). We have very good evidence that in the absence of this sensory nervous stream the neurones supplying muscles and glands cannot work at all, except when acted on by potent artificial stimuli, such as a strong electrical current or drugs, and all so-called conscious cerebral processes cease. With the exception of the respiratory center in the medulla oblongata, which is a group of neurones that is capable of acting in response to the carbon dioxide in the blood, and in the absence of sensory impulses, there appears to be no such a thing as "automatic action" in the central nervous system. In man and the rest of the higher animals, at least, all the special processes in (if not the very life of) the differentiated central nervous system, are as dependent on the continuous physico-chemical influence of the subconscious sensory system as the skeletal muscle tonus is dependent on the reflex arcs. Some of the large aggregates or parts in the central nervous system appear to be differentiated in the direction of augmenting or otherwise regulating this central tonus, despite the fact that it is primarily dependent on sensory impulses. Thus we find that removal of the cerebellum decreases the ability of the spinal cord to modify the skeletal tonus reflexes; severance of the spinal cord from the influence of the medulla leads to failure of the vaso-constrictor reflexes; and removal of the cerebrum causes, for a time, a great augmentation of the skeletal muscle tonus reflexes, a condition known as decerebrate rigidity.

The foregoing facts challenge ancient and modern theories of

CHAPTER XVII

MIND IN EVOLUTION

CHARLES HUBBARD JUDD

SCIENTIFIC STUDIES OF HUMAN NATURE

Consciousness as distinct from physical processes.—The world as science describes it is very different from the world which one sees and feels and hears. To the eye white light seems as simple as red or blue, and there is no intimation in direct visual experience that the colors are due to vibrations. To the hand a bar of steel does not seem to be made up of minute particles with spaces between them and still less is there any indication of movements within the mass. We might go on indefinitely citing cases to show that the statements of science are very different from the sensory impressions which come to the mind of an observer.

The scientific problem of explaining mental life.—There was a time in the comparatively recent history of our race when men were haled before courts and exiled for making scientific statements which ran counter to popular belief. We are disposed in this modern age to regard the inquisitors of medieval days as bigoted and fanatical. The fact is that they were shocked beyond all degree at the attack which the early scientists made on their perfectly clear and seemingly reliable observations. When men of the sixteenth century were told that the earth is moving through space at an incredible speed, they thought it well for the peace of their times to put an end to that kind of dangerous attack on what they believed to be the most substantial and fixed fact of experience. They argued that anyone who could believe such a preposterous doctrine might at any time take steps to invade the rights of property or might attack the government and certainly was unfriendly to the church. Men's beliefs in that period were those which depended directly on their senses. If the

earth seemed solid, it was to be thought of as solid. If the earth seemed to be the center of the universe and seemed to stand still, anyone who preached a doctrine of any other type was an enemy of society.

This is not the place for a review of the long history of mental and social struggles by which man has freed himself from direct reliance on his senses and has reached the point where he can reconstruct the world by processes of reasoning, arriving at a conception of reality which is totally different from anything that he can hope ever to see or handle. It is enough for our present purpose to point out that as the natural sciences were developed, a new problem became increasingly clear; it is the problem of explaining the nature of human experience. If white light looks simple when it is in fact complex, then we must explain, if we are to be truly scientific and complete in our understanding of the world, both facts, namely the apparent simplicity of white light and its actual complexity.

Early scientific efforts to discover the relation of mind and physical processes.—Perhaps it will make the point clearer if we refer to the historical fact that some of the students of human nature of the last century called themselves psychophysicists. They set for themselves the task of explaining the relation between mental, or psychical, phenomena and physical phenomena, and they found as the earliest results of their work that the laws of the inner world of man's experience differ from the laws of physical nature. They found that it does not always follow that a change in the external world produces a change in the mental world; furthermore, when there are related changes in both worlds, they are not always of the same degree or even of the same kind. For example, if one increases the frequency of vibrations of a musical instrument, the change in the outer world is a quantitative change, while the change in experience is a qualitative change described in the statement that vibrations of high frequency produce in experience a high-pitched tone, while vibrations of lower frequency produce a lower-pitched tone.

The province of psychology.—Our task, in these lectures on the science of psychology and its contributions to an understanding of man's place in the world, is to sketch some of the reasons why consciousness differs from the facts in the outside world and to point out some of the characteristics of the inner world.

THE NERVOUS SYSTEM AND CONSCIOUSNESS

Physiological and comparative psychology.—One of the methods which modern psychology has found it advantageous to adopt in its investigations is that of approaching the individual's mental life from the outside. The student of mental life who works in a modern psychological laboratory does not limit his investigations to the direct testimony of individuals about their mental processes. The psychologist watches the person whom he is studying and devises ways of securing records of his reactions to the impressions which are given to him. The psychologist joins with the physiologist in studying the nervous structures on the action of which consciousness depends. By these methods it is possible in the long run to tell the individual more about himself than he knows.

In approaching man's mind from the outside we may begin with a study of the organs of the body which are most directly related to conscious life, namely, the sense organs and the organs of the central nervous system. From the structures of these organs we can form some very useful ideas as to the way in which human nature and the world are related. The name "physiological psychology" has been used in recent years to designate the branch of psychology which deals with the nervous system.

Some of the studies of physiological psychology take up the examination of animal nervous systems and their functions. The name "comparative psychology" has been used to cover those investigations of structural facts and facts of behavior which contribute to an understanding of the relation of human mental life to the inner life of the other animals.

Sensitivity a fundamental organic function.—If we study even the lowest animal forms we find that they exhibit a charac-

teristic which we call sensitivity. If one of the unicellular forms encounters a resistant object as it moves about in the process of securing food, if it passes out of a dimly lighted area into a brightly lighted area, if the surrounding temperature changes, there is set up within the protoplasmic mass an agitation which constitutes the animal's reaction to the external stimulus. Whatever the form of this internal agitation may be, one fact is quite certain, the internal agitation is not like the external force which produced it. The responses of protoplasm to light and other stimuli are not light or repetitions of the external facts, but protoplasmic commotion of some kind. Consciousness in turn is not the same in character as the protoplasmic commotion. We see thus at the outset of our study the reason why individual experience is so far removed from being a mere reproduction of the outer world. An individual's experience records his own state resulting from his own nature and its reactions in the presence of external facts; experience does not reproduce external facts.

Gradual differentiation of sensitivity.—Recent studies show that even in the lowest known forms of animal life the inner protoplasmic reactions are not altogether undifferentiated. Apparently what happens in the protoplasm when light excites action is different from the process excited by contact of the protoplasm with a solid object which the animal encounters. Differentiation of response does not go as far, however, in the lower forms as in the higher animals. The higher animals are more responsive to different kinds of stimulations because they have organs which respond vigorously to different kinds of stimulations. Thus in man there are two specialized parts of the body which respond vigorously to sound vibrations, that is, the ears; there are two parts, namely the eyes, which respond to light stimulations.

The processes of evolution through which these special organs of sense have been produced and selected are similar to the processes by which all the organs of the higher animals have gradually evolved from the unicellular forms of animal life.

In general terms, it may said that certain cells on the surface

of the body gradually become differentiated so as to respond to a number of particular stimuli.

Rudimentary visual organs.—For example, in the outer body wall of the jellyfishes certain spots made up of pigmented cells are adapted to the special function of responding vigorously to light stimulations. The pigment in these spots contributes to the absorption of the light and much more energetic photochemical processes are set up in the cells than in the neighboring cells of the body wall. These pigment spots are rudimentary eyes. This primitive eye does not form an image, as our eye does, for it has no optical chamber and no lens. Its internal processes are more like the vague discriminations of light and shadow which a human being gets through closed eyelids. It is, however, of great biological advantage to the animal as a guide to places where plants grow and where there is food. Darkness means no food, but sometimes protection. So the jellyfish with the primitive pigment spot is advantaged in the struggle for existence.

The evolution of the organ which responds to light has followed various lines in different animal groups. A very striking series of progressively complex forms can be made up by examining the mollusks (the snail-shellfish group, see p. 275).

There is at the lowest levels, as in the jellyfishes, a pigmented spot on the surface of the body made up of cells differing little in appearance from the epithelial cells which make up the body wall. At the next stage the pigmented cells have receded into a protecting pocket. This pocket is large in some of the forms and in some cases filled with a translucent gelatinous substance. In the course of evolution this substance becomes increasingly transparent. Ultimately a lens is formed. The earliest type of lens is a crude spherical structure and quite inflexible. Later the lens is refined in form, and in the highest animals is supplied with muscles which change its form so as to focus clearly defined images on the sensory cells.

Complex character of the human eye.—The human eye is a highly evolved optical organ. Its lens is double convex and is

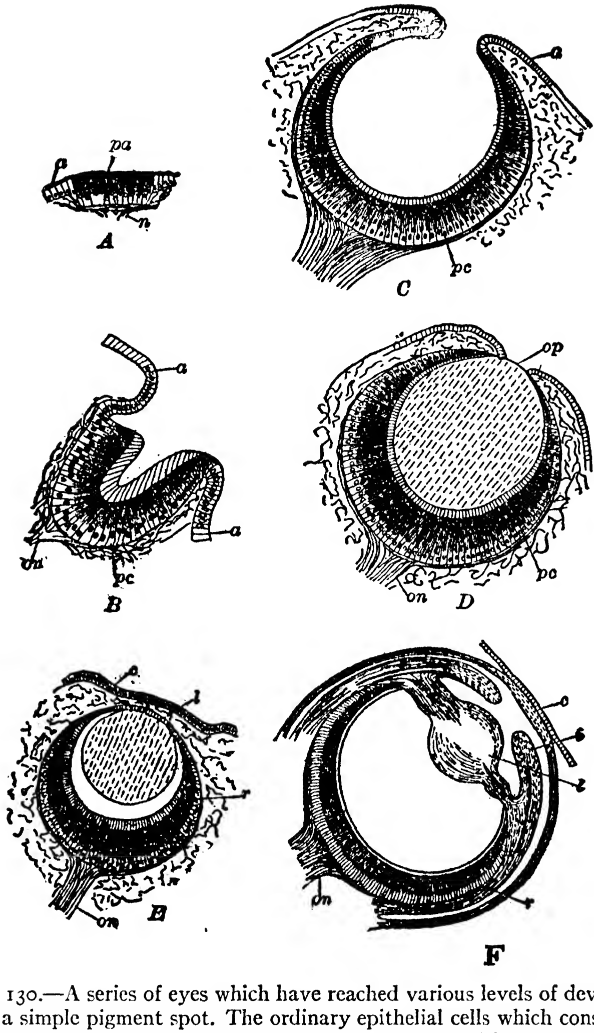


FIG. 130.—A series of eyes which have reached various levels of development. *A* shows a simple pigment spot. The ordinary epithelial cells which constitute the surface of the body are represented at *a*. The pigment particles represented at *pa* make this portion of the surface of the body more susceptible to the action of light. *B* shows a somewhat more highly developed organ. The surface of the body is here depressed so as to protect the sensory cells. These specialized cells are notably larger than the epithelial cells at *aa*. This is the eye of Patelia. *C* represents the eye of Nautilus. The central cavity is filled with water. *D* is a camera eye with a large lens filling its cavity; *op* represents the lens. *E* is the camera eye of Murex with the cornea, *c*, covering the lens. *F* is the complete eye of cuttlefish with the lens, *l*; cornea, *c*; iris, *i*, and other portions as before. (From Conn's *Method of Evolution.*)

supplied with complex muscles which change its degree of convexity for near and far objects. The eyeball is detached also from the general body wall and is supplied with muscles which turn the eye in any direction necessary to respond to stimulations.

This refinement of the optical part of the eye is accompanied by a refinement and differentiation of the nervous organs. The edge of the human retina is supplied with cells capable of only a limited number of different photochemical processes, while the center of the retina has more highly evolved cells capable of responding in much more highly differentiated ways to different kinds of light stimulations, such as the different colors.

Color-blindness and its meaning.—We infer the way in which the highly differentiated photochemical processes in the human eye have been evolved by a study of certain cases in which human beings are only partially competent in color discriminations. Such persons are said to be color-blind (cf. p. 425). Their retinal processes in the central area, where color responses are normally fully differentiated, are only partially differentiated. The most common form of color-blindness is that in which the individual cannot distinguish red from green. These two colors, which are clearly distinguished from one another by the normal person, are seen as a single straw color by the color-blind person. There is a less common form of color-blindness in which none of the colors is distinguished from any other. The person sees the world as a series of shades of gray.

Limits of sensitivity.—It is important to note at this point in the discussion two general facts. One is that even the most highly evolved eyes respond to only a narrow range of light vibrations. The ultra-violet rays are invisible to our eyes. This means that the cells in our eyes do not respond to ultra-violet rays with the type of chemical processes which produce sensations. There is also a long range of infra-red rays to which our eyes do not respond. The limitations of our vision may be described by saying that physical light vibrations extend over fifty-five octaves, whereas our eyes are sensitive to a single octave. Here is another

example of the fact mentioned earlier: the inner experience of an animal is not a reproduction of the outer world but is an expression of the animal's ability to respond by some form of internal reaction.

Sensitivity as related to behavior.—The second general fact is that the range of an animal's sensitivity is directly related to the sphere of its life. The ability which a human being normally possesses of discriminating between red and green is useful in guiding the individual in distinguishing between such objects as ripe fruit and unripe. The lack of ability to respond to infra-red rays means that human beings do not respond in their reactions to external conditions which produce these rays.

Evolution of other senses.—What has been said about the organ of vision can be said in much the same terms for the other senses. The surface of the body of all animals is from the first sensitive to contacts, to heat and cold, very much as our skin is. Differentiation has taken place in the course of evolution resulting in specialized senses of taste, smell, hearing, and vision.

Some of the characteristics which distinguish the human senses from those of the animals are of interest. Hearing is an important human sense because it records the fine shades of sound required for human speech. It serves chiefly as a location-sense in some other animal forms. The horse, for example, locates sounds by moving its outer ear in various directions. The funnel-shaped ear of the horse is very useful in locating sounds because the funnel can be moved in various directions. But the funnel is a disadvantage in discriminating sounds for it dulls somewhat the fine qualitative differences of sounds. The much reduced form of the human external ear makes it less useful as a location-sense, but greatly enhances its value for qualitative discriminations.

Forces for which there are no human senses.—What has been said about the adaptation of an animal's senses to its sphere of life can perhaps be reinforced by calling attention to the fact that there are groups of real forces for which we have no sense whatsoever. We have no sense for such forms of energy as the X-rays

Our knowledge of the existence of these forms of energy is, accordingly, relatively recent and dependent on the ability of science to transform X-rays into other types of energy which come within the range of our senses.

Extension of sensory experience.—There are extensions of our senses besides those which bring to our knowledge such forms of energy as X-rays. We have microscopes and telescopes. By means of these instruments our knowledge of the universe has been greatly extended, and through the use of such instruments science has arrived at an understanding of a world utterly unknown to the unaided human senses. This extension of experience has led us to adopt many new modes of action which can properly be described as superior to our natural modes of response to the world. Man's extensions of his sensory world have made him a superior member of the animal kingdom. He has learned how to transcend the sphere of life for which his unaided senses are adapted.

Contrast between human senses and animal senses.—Some animals have senses which reveal to them facts for which we have no direct sensory experience. The spiders, for example, have microscopic eyes. Such eyes would be of very restricted use in a human body because we have no organs of manipulation with which to respond directly to microscopic objects. When we extend our experience by the use of optical instruments so as to see microscopic objects, we find it necessary to invent also artificial means of dealing with these objects.

We see now a larger meaning in the statement with which we began this discussion. The organs of sense of any animal are specialized parts of that animal's body. They contribute to the animal's life by serving as centers of first response to those external forces which are of most immediate and vital importance to that particular animal.

Organs of reaction.—We turn now from the sense organs to a consideration of the organs of reaction. The word reaction has been used in a number of connections in the foregoing paragraphs.

An animal is not a passive object on which the forces of nature impinge. It is an active being capable of releasing energy and of exerting force upon objects. It is also capable of taking substances into its body and producing chemical changes; especially is it capable of absorbing these foreign substances as food. The active side of an animal's nature is as characteristic as its ability to receive impressions. Indeed, as we have seen, the receiving of impressions is itself a type of chemical reaction.

The power of an animal actively to attack the substances in its environment is localized in specialized cells. Some of these specialized cells are chemical reactors; these we call in general glands. Some of the active organs have as their function the movement of the animal's body; these we call muscles.

The muscles and some of the glands in all of the higher animals react under normal conditions as a result of nervous impulses which originate in the sensitive receiving cells which have been described in foregoing paragraphs.

Relation of sensory cells and reacting cells.—In the less complex multicellular organisms the muscles and sensory cells are directly related, and impulses travel over from the sensory cells directly. In the more complex animals the mechanism for stimulating the active organs is much more complex. The sensory cells transmit impulses to certain central cells, which in turn send the impulses on to the active organs.

Let us consider as a typical example of one of the simpler central nervous systems that of the earthworm. In each of the segments of the earthworm's body there is a ganglion, as it is called, or knot, of central cells to which the sensory cells at the surface of that particular segment send impulses and from which motor stimulations are sent to the active cells. The ganglion of one segment is connected with the ganglion of the next neighboring segment by a bundle of fibers. The nervous system at this stage consists of two types of cells: sensory cells at the surface of the body and central transmitting cells within the body. The central ganglion of one segment is a kind of switchboard for the

incoming and outgoing stimulations. It is a center of control for that particular segment, and is also the means of integrating one segment with the others which make up the animal's body.

The higher nervous center as an organ of integration.—In the earthworm one of the forward segments of the body develops a ganglionic center of superior size and importance. This important center is near the mouth and operates to control the whole body in the interests of the food-taking function. In general, it is found throughout the higher animal groups that a superior central part of the nervous system exercises control over the whole body.

This superior central control results in a unification of the action of the whole body. One of the leading investigators of the nervous system refers to this and related facts as the integrative action of the nervous system. In the higher animals a flash of light falling on the eye or a faint sound striking the ear is transmitted from the surface of the body to the central nerve cells. Here it is directed by a series of central connections into channels of discharge and ultimately transmitted to remote parts of the body so that legs and arms and heart and respiratory system are all called into action promptly and effectively to meet the demands which arise from the sensory stimulation.

Memory.—The central nervous system of an animal's body serves a purpose additional to the integration of the body. It becomes a center for the retention of traces of past action. Such traces are preserved and turned to the animal's advantage or, as sometimes happens, to the animal's disadvantage. We do not know exactly the way in which this process of retaining traces of past experience goes on. Some change in the minute molecular arrangement of nerve cells undoubtedly occurs. We have to infer what goes on from the way in which an animal behaves. When an animal has been fed in a certain place, we know that it will tend to come back to that place. We say that the first stimulation has so marked paths through the nerve cells that a new stimulation of hunger or a new odor of food travels through the nerve

cells to the muscles and produces an action like the first. All this is but saying in terms of nervous structure what we describe in ordinary life and in science by the name habit. The nervous system is the seat of habits. When nerve cells have acted in a certain way, they act more easily the second time and the third time in the same fashion.

Instincts as inherited nervous patterns.—We know also that the central nervous system has certain patterns which are transmitted from generation to generation in the same way that the pattern of the human hand and the pattern of human features are transmitted. Thus all the higher animals have the nervous mechanism, as well as the muscles, necessary for swallowing and also for dodging to protect the head and eyes from danger. These activities are so essential to life that they are transmitted through inheritance just as are the long legs of the horse and the wings of a bird. A nervous tract thus established and transmitted is known as an instinct.

Disadvantageous nervous patterns.—It was remarked a moment ago that a fixed path through a nervous system may operate to the disadvantage of its possessor. Think, for example, of the proverbial moth and the destructive flame. The moth possesses as a result of inheritance a nervous system which responds positively to light. This positive reaction has in the past been of no disadvantage to moths and may have been of some advantage to their kind. At all events, the moths have a fixed and strong tendency to move toward a bright spot of light. Under the conditions created by man with his lighted tapers this proves to be a serious disadvantage to the moths. The nervous pattern is, however, so fixed that it is not changed as a result of individual experience. Here, then, is an instinct which, under existing conditions, is disadvantageous to its possessor.

What is true of instincts is often true of patterns in the nervous system which are acquired through individual experience. Acquired patterns are advantageous in that they facilitate adjustments; they are disadvantageous in that they sometimes become

fixed and inflexible. Kipling has put the matter in a very impressive way in his account of the famine in India. The natives were unable to secure the rice which they knew how to grind and eat. The government sent them corn, but the fixed habits of a lifetime were too strong to be overcome even to save life. The natives grumbled about the corn, saying that it was coarse and hurt their teeth and they died as has many another animal species because of the inflexible paths through their nervous systems. The fact is that much human action is of the type here illustrated, fixed by habit rather than controlled by reason.

The adaptive character of habits and instincts.—While some fixed paths through the nervous system have disadvantages of the kind described, most such paths yield enormous advantages. When an animal has performed a certain act or series of acts and has survived, it is altogether probable that it will be advantaged by doing something of the same kind again. There may be a few cases in which repeated activities are merely indifferent, but in general they represent successes. Instincts and habits are to be thought of in general as records of successes, which are of long standing. Swallowing is an ancient performance and is transmitted from generation to generation in fully developed form. Habits are records of recent successes. They represent the adaptations of an individual to the special environment which surrounds him.

Relation of acquired reactions to instincts.—There is a certain antithesis between instinct and habit. If an animal is dominated by an instinct there is no need of a habit in the particular situation in which the instinct operates. If, on the other hand, an inherited instinctive mode of behavior is not altogether appropriate in the individual's environment, habit will have to replace instinct.

Modification of behavior through experience.—It is found that all animals can modify to some extent their instinctive modes of reaction. This process of changing the inherited nervous pattern sometimes costs a struggle, but it gives the individual a wider possibility of adaptation. It releases the individual from the

dangers of fixity of action. The struggle to modify an instinctive adjustment can be illustrated by an example taken from human life. In a human infant it is found that the act of grasping by closing the fingers all together against the palm of the hand is an instinctive act. This natural form of response must be changed in order to provide for the manipulation of any tool. To use a pen, for example, requires the development of a habit of holding the highly artificial tool between the fingers. A skilful habit of thus holding the pen can be acquired only after a period of struggle to break up the instinct. The first result of this struggle is a period of diffuse movement. Diffuse movement is followed by selection through trial and error of the component elements of action necessary to the refined form of manipulation.

Importance of individual adaptations.—So advantageous is flexibility of motor and nervous adjustment that there has appeared in the course of animal evolution an ever increasing degree of flexibility or adaptability of behavior. The central nervous system has been enlarged until it includes two types of nervous patterns. On the one hand, there are fixed inherited patterns which control necessary and relatively unchanging forms of behavior, and, on the other hand, there are areas of the highest parts of the nervous system that are not fixed by inheritance, but are left to be mapped out in the course of individual experience. Indeed, an interesting fact is that of the two functions, individual adaptation is the more important when we consider the characteristic and significant adaptations in the highest of the animals, especially the adaptations in our race.

Comparative characteristics of vertebrate nervous systems.—The matter can be made clearer by a figure showing the relation of the nervous structures of one of the higher vertebrates such as the dog to those of the lower vertebrate forms. In the dog the cerebrum is comparatively very large.

All vertebrates have spinal cords. The spinal cord is a group of cells and connecting nerve fibers which occupy a position in the dorsal part of the body. To the central nervous cells in the cord

come sensory impulses from the sensory cells of the skin, of the joints, and of the muscles. The incoming sensory stimulations which reach these central cells are sent back to the muscles in what are technically known as reflexes. The spinal cord of man is the organ which provides that the hand shall be drawn back quickly if it is brought into contact with something hot. The reflex jerking back in such a case is a natural and desirable move-

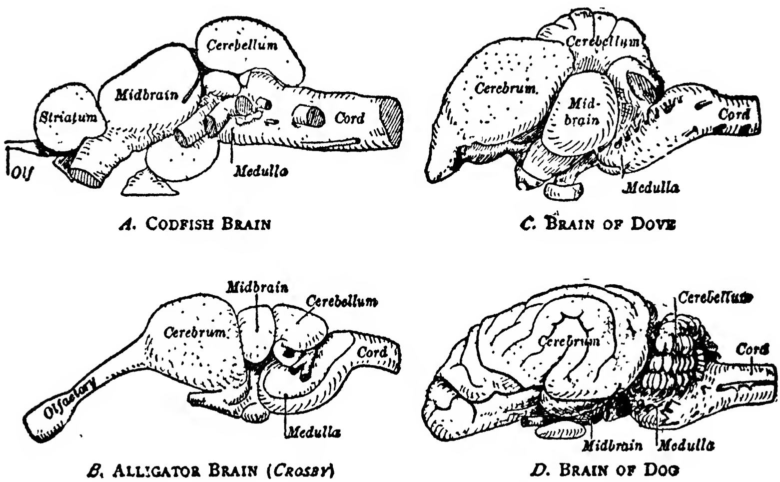


FIG. 131.—Plate showing successive stages in the evolution of the vertebrate nervous system (especially conspicuous is the increase in size and importance of the indirect centers, the cerebellum and cerebrum).

ment of self-protection. Every individual's nervous system is provided at birth with this inherited, highly fixed, and relatively simple mechanism.

All vertebrates have at the upper end of the spinal cord an enlargement known as the medulla oblongata. Here are the centers which keep the breathing mechanism at work. Here also is the center which takes care of swallowing and like forms of complex automatic behavior.

Every vertebrate has still higher centers of automatic adjustment above the medulla. In these higher centers are the nervous

mechanisms which adjust the lens of the eye and provide the protective movements, such as the movement of throwing out the hands when one is falling.

The centers of automatic and reflex adjustment differ in size and relative importance in the vertebrates in accordance with the spheres of the animals' life. Those animals which, like the frog, depend largely on adaptations involving vision have large centers connected with the eyes. Those animals which have complex co-ordinations in their locomotion, such as the birds and the cat tribe, have elaborate cerebellums. In general, we look for size in those parts of the central nervous system which are of the greatest functional importance.

All these considerations lead to an understanding of the characteristic fact with regard to the central nervous system of man. Man has a spinal cord, a medulla, basal ganglia, and a cerebellum. These are in his case, as in the cases of the other vertebrates, centers of reflex and automatic adjustment. Man has instincts and automatic forms of behavior which are absolutely essential to his life. These inherited forms of behavior protect him in the early days of infancy and provide in later life the basic adjustments necessary to existence.

The unique importance of the cerebrum.—The parts of the vertebrate nervous systems thus far described furnish little or no clue to man's unique place in the world. For an understanding of man's mode of life one must turn from the reflex and automatic centers to a part of the nervous system which stands out in any comparative series as the distinctive structure in the brains of the more complex vertebrates, especially man. This highly significant part of the central nervous system is the cerebrum.

The fishes and amphibians have relatively very few cerebral cells. The birds and mammals show distinct superiority in the size of the cerebrum and in the number of cerebral cells. The Primates have the highest development of the cerebrum. The cerebrum is the most characteristic of the human organs. If we knew nothing more about the cerebrum than that which we can

discover from a study of the comparative series of vertebrate nervous systems, we should be quite certain that we have in this organ one of the most important elements of human nature.

Methods of study of nervous structure.—Modern science has been able to make some headway in the study of the minute inner structure of the cerebrum, and has also been able to determine the functions of some of its parts with a high degree of precision. It may be well to point out briefly the methods by which facts of this type have been secured.

The cerebrum is made up in part of connective tissue. Held in this connective tissue are neurones, or true nerve cells, each one of which is made up of a central mass of protoplasm and of branches. The central cell body varies in diameter from 1/2500 to 1/3500 of an inch. We should be helpless in distinguishing the various structures of the nervous system if it were not for certain methods of staining which enable us to differentiate the various structures from one another. Especially important is the method discovered in 1882, by Golgi, by means of which the nerve cells can be clearly distinguished from the rest of the tissue. Microscopic examination has shown where the cells are and something of their connections.

Microscopic examination is aided in distinguishing the various structures which make up the nerve tissues by the fact that certain parts of the cerebrum come to full maturity before other parts. The different stages of maturity can be seen in the stained specimens and it is thus possible to discover related areas. The study of brains at different stages of infant development is, therefore, very instructive.

A method of distinguishing the different structures no less important than that which was discovered by studying individual development is that which depends on the tracing of structural degeneration. When pathological conditions destroy some part of the brain, all the related parts are relatively easy to trace because they deteriorate in sympathy with the part primarily affected.

The cerebrum as a super-central organ.—As a result of the applications of the methods of investigation thus described, we know that the cerebrum is a super-central organ. It is not in most of its parts a seat of reflex adjustments, as are the lower parts of the nervous system. It receives stimulations indirectly from the lower centers and sends motor impulses to the active organs of the body indirectly through the lower centers. The cerebrum is, in the main, an organ of integration of the lower nervous centers.

The cerebrum and individual experience.—The cerebrum is, also, more than any other part of the nervous system, modified by individual experience. Whenever sensory impulses reach the cerebrum and are transmitted to the motor centers from which they are discharged, changes take place within the cerebrum which affect all the subsequent life of the organism. This is the physical fact corresponding to that which we know in personal experience as memory. The cerebrum is less completely mapped out by inheritance than are any of the other organs of the nervous system. It is so little matured at birth and of such preponderating importance in determining behavior that the human infant is the most helpless of living creatures. John Fisk pointed out in his essay on the *Meaning of Infancy* that the period of helplessness increases steadily as animals increase in individual adaptability. The fact that human infants go through a long period of helplessness is directly related to the large areas of nervous tissue in the infant's higher nervous centers which are not mapped out by inheritance, but are left to be determined in structure by individual experience.

UNIQUE CHARACTERISTICS OF MAN

Man a part of the evolutionary series.—When human adaptations are described as having a special character it should be clearly understood that there is no intimation in the statement that man represents a break in the evolutionary series. The size of the cerebrum, its inner structure and its connections with the other parts of the nervous system, and its functions are products of

evolution. The general pattern of the nerve cells in the cerebrum is not unlike that of cells in the other parts of the nervous system, but the cerebrum is an assemblage of nerve cells in a highly complex organ. This organ is so related to the other parts of the nervous system that it exhibits unique functions. It is an integrating organ of the highest importance. It is an organ of individual adaptations or of variable adaptations. It is an organ closely related to conscious experience. It is the structure which more than any other accounts for man's place in the evolutionary series. To its unique functions we must trace that which most completely distinguishes man from the other animals.

Speech as an example of higher forms of adaptation.—The difference between the adaptations which are developed in the course of individual life, and have their seats in the cerebrum, and the adaptations of the reflex and instinctive types can be made clear by an examination of the function of speech.

The speech functions are among the latest and most highly variable forms of activity produced by evolution. So variable are the speech activities that a child can learn with equal ease English or Chinese. Speech is a series of cultivated habits which the child takes on by imitating its environment. The nervous centers involved in speech are in the cerebrum. In this organ are tracts running from the points of reception of visual and auditory impressions to areas where the sensory impulses flow together and are united. From these centers of union, or association centers as they are called, the impulses are carried to certain motor centers from which they are sent down to the vocal cords.

Other higher modes of adaptation.—Speech is a characteristic function of the cerebrum. We must conceive of the inner processes of reasoning as related to elaborate systems of organized tracts in the cerebrum similar to those involved in speech. It is through the functioning of such cerebral tracts that man has been able to achieve through mechanical invention and scientific thought the supreme place which he occupies in the world. It is in the cerebrum, rather than in the lower reflex and automatic centers, that

the new combinations of sensory and motor impulses have been worked out which give to man the degree of mastery of his environment which he has thus far achieved. In the presence of cold, man exhibited sufficient originality of reaction to do what no animal before him had done: he used fire. This new method of adapting himself to his environment made it unnecessary for him to modify his physical structures, as many species of animals lower in the scale of life have done in adjusting themselves to cold.

We do not know how long it required for man to develop the use of fire. That volcanic sources of fire were regarded as sacred shrines by many primitive nations is evidence that fire was first discovered by man in those places where nature provided it. Once fire was mastered, man evidently exerted himself to preserve it. This is shown to be true by the elaborate religious ceremonials which surround the priestly use and dispensation of fire, and by the fact that fire is extensively employed in religious rites such as sacrifice and purification.

The mythology which surrounds the use of fire shows that man came very gradually to an understanding of the methods of controlling his environment, but during the long ages which elapsed between the early use of fire and our present scientific knowledge about combustion, man has been a being controlled characteristically by his higher nervous centers and by his acquired modes of reaction, not by his inherited instincts. Man has instincts in abundance. He is afraid like other animals, he runs from danger, and he grows enraged, and he fights. His heart increases in the rate of its action and some of his glands are affected when he is emotionally excited. These are, however, not his highest and most significant reactions. Man, the user of fire; man, the user of tools; man, the inventor of machinery; man, who has devised elaborate forms of government, is not following instinctive, inherited patterns of behavior. He is, rather, an animal who exhibits a broader and more inclusive form of attention than has been exhibited by any of the other forms of animal life. He uses a cerebrum in which the associative processes, which combine and

recombine nervous impulses, are the typical and significant facts in his life.

The evolution of intelligence.—It is not denied by any means that many of the animals use their cerebrums in developing complex and often somewhat original forms of reaction. It is, however, evident from comparative studies that no animal below the human race has become so completely cerebrated and so characteristically inventive as has *Homo sapiens*. Animals do not typically use tools and they do not pass the lowest stages of mechanical invention. They do not evolve speech and they have no science. Man lives in a world of social institutions such as number, weights and measures, time measurements, and the fine arts, which distinguish him sharply from his nearest relatives in the animal kingdom.

Branches of psychology other than physiological psychology.—Thus far in our study we have made liberal use of the methods of physiological psychology. We have seen something of the evolution of the organs of sense and of the central nervous system, and we have in this way learned much about the ways in which the animals and man adapt themselves to the world. The methods of physiological psychology cannot, however, give us a complete understanding of human nature. There are many processes of inner co-ordination and external behavior which are far too subtle to be studied by physiological methods. We are compelled to extend our study through the use of experimental methods. That branch of psychology by which we extend our knowledge of human nature beyond what we can learn through a study of the nervous structures is called "experimental psychology." In addition to experimental methods, psychology uses also the methods of anthropology and history, thus developing what is known as "social psychology." Finally, through direct appeal to the testimony which human beings are able to give of the happenings in their own conscious experiences there is developed what we know as "introspective psychology."

Experimental psychology, social psychology, and introspec-

tive psychology are not separate sciences but branches of one general science, distinguished from one another by their emphasis on methods of investigation. Like physiological psychology, these branches of the general science are devoted to the explanation of man's evolution and adaptation of himself to the world in which he lives.

We may advance the general discussion by describing certain typical facts borrowed from each of the subdivisions of our science.

EXPERIMENTAL PSYCHOLOGY

Animal learning.—For the purpose of illustrating experimental psychology, we may begin by referring to the use of experimental methods in studying animal adaptations. An animal is put in front of two openings. If he goes through one he will be rewarded with food, if he goes through the other he will receive no food. The food opening is colored red and the opening which leads to no food is colored green. By the use of various colors it has been shown that animal perceptions of color differences are more acute in some respects and less acute in others than are the color perceptions of human beings.

Like methods are used to secure measures of the rate at which animals learn other forms of individual reaction. A fairly definite scale of flexibility in adaptations can be established by measuring the rapidity with which various species learn to react under comparable conditions.

Human learning.—Some of the most interesting and valuable results of experimental psychology have been secured by measuring the details of progress and rate of human learning. An example is as follows. The rate at which a learner acquired the ability to receive and send telegraphic messages was measured and the records were assembled in a graph. This graph is shown in Figure 132.

It will be noted that the lines in both the sending and receiving curves rise rapidly at first and finally reach a level where further practice produces no apparent improvement. The two curves are

strikingly different in form. The sending curve rises in a somewhat irregular, but uninterrupted, convex form and maintains throughout a higher level than does the receiving curve. The receiving curve has two distinct phases. It rises to a level where for a time no improvement appears and, after remaining at this level during a considerable interval, rises again. The period during

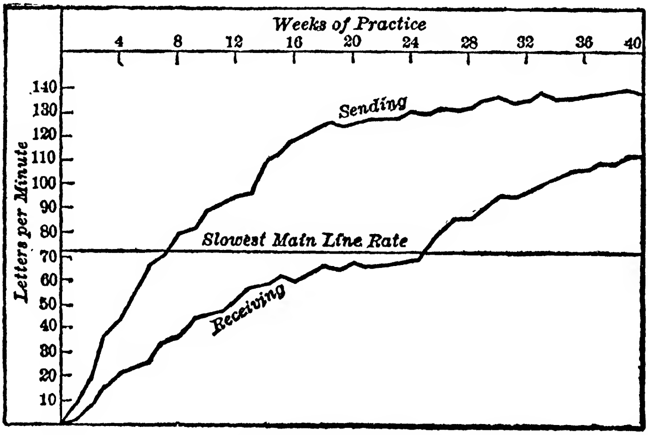


FIG. 132.—Curves for sending and receiving telegraphic messages. The curve is published by Bryan and Harter. The number of weeks of practice is indicated in the upper part of the figure. The number of letters which can be received and sent in a minute is represented in the vertical. The figure is divided by a horizontal line, which shows the standard rate.

which there is little or no improvement was called by the investigators who carried on this experiment, a learning plateau.

The learning process may safely be assumed to involve complex changes in the cerebrum, but we have no direct knowledge from studies of brain anatomy of what these changes are. We know from extirpations made on animals and from a study of human pathology something of the locations in the cerebrum of the changes, whatever they are, which take place during learning processes, but such details as are brought out in the graph carry our knowledge far beyond anything shown by the microscope.

Furthermore, by pursuing the experiment and analyzing the

way in which learners develop their abilities, it is possible to reach an explanation of the differences between the sending and receiving curves. The receiving of a message is slow at first because attention is centered on individual letters. Gradually the learner becomes familiar enough with letters so that he can attend to words. He remains at this stage for a long time. He is passing through a period of assimilation. This is what accounts for the plateau. Finally, he reaches the point where he can grasp a whole series of words much as a trained reader does in looking at a printed line. At this stage the expert receiver does not hear the letters as separate items, but as part of a larger whole. This ability to get away from the separate elements of experience and deal with wholes is a late and mature acquisition. As shown in the experiment, it comes as a second phase of the learning process.

Plateaus in the learning curve.—The special form of the sending curve is explained by the fact that the operator knows in advance by virtue of his earlier mastery of language what he is going to do. He knows each letter which he is to send before he begins to send it. His attention is accordingly freer than when he is receiving letters which come from an outside source.

We are not so much concerned for our present purposes with the contrast between the two learning curves as we are with the fact that human nature can be studied and a record of its performances can be made so as to reveal the ways in which human beings acquire experience.

Experiments in learning without direct practical motives.—Similar records have been made in a great many different spheres of learning, and we now have a fairly complete knowledge of the way in which mental processes are carried on in a great variety of circumstances.

In some cases psychology has found it desirable for theoretical reasons to study the laws of human learning under conditions which yield no direct practical results. For example, one psychologist wore for a period of time a system of reflecting prisms before his eyes which turned the world upside down. He wore

those prisms until he became fully adapted to the new type of visual experience. Another psychologist put himself through the wholly impractical task of learning meaningless syllables, or as they are called, nonsense syllables, like *baf*. These are made up for the purpose of studying the laws of remembering and forgetting under conditions which avoid all of the accidental distractions which would follow if meaningful words were used. Since the invention of nonsense syllables, they have been used in a great variety of significant experiments on memory.

Methods of learning based on experimental studies.—The foregoing examples give some idea of what is meant by the experimental method. It may be remarked that what was known about human methods of learning before experimental methods were adopted was very meager as contrasted with the large body of facts which has been accumulated in recent years in psychological laboratories. It is quite as true in psychology, as it is in the other sciences, that systematic study has changed men's conception of the facts and has led to a scientific understanding which is often very different from the view derived from ordinary observation. For example, we know that it is more economical to learn a poem of ten stanzas by reading it through again and again than it is to learn it line by line. The part-learning method seems natural and economical, but it is not. We have, then, in psychology, no less than in the natural sciences, a body of concepts which differ from the ideas derived from direct observation. It seems strange to some people that the psychologist should venture assertions about human mental life which do not seem to tally with one's unscientific notions. Here, as in all fields of knowledge, science is more comprehensive than direct observation, and inferences based on a large body of carefully collected facts are safer than the conclusions which seem to issue from momentary and limited experience.

CIVILIZATION AS A PRODUCT OF INTELLIGENCE

Social psychology.—The studies made by social psychology are as productive as are those made by experimental methods.

The anthropological and historical records of human life show that the great advances in men's knowledge and methods of dealing with the world have come through social co-operation. Men have accomplished in groups what isolated individuals could not possibly have achieved.

Tools as products of intelligence.—Perhaps the most concrete example of effective social co-operation is to be found in the evolution of the mechanical arts. For generations men have been inventing and perfecting tools, and through the use of tools they have transformed in very large measure the world in which they live. How distinctly the making and using of tools belongs to the world of human adaptations is shown by the fact that animals are typically dependent upon the direct use of their own organs and do not produce machinery. Indeed, animals do not have tools at all unless we record as exceptions to this statement the use here and there in a sporadic and isolated way of a missile or a lever or some other primitive natural tool. The typical fact in animal life below man is direct attack on every object dealt with, not indirect mechanical attack. No animal ever used a bow and arrow. No animal ever used a wheel.

The way in which intelligence operated in the discovery of tools is revealed in the earliest anthropological records. The first tools are nothing but natural objects put to a new use. Some of the earliest tools were a sharp stone used as a knife, a gnarled root or a heavy bone used as a club, and a thorn or sharp bone used as a needle. All of these usable objects had existed in nature long before men adopted them as tools.

It is not improbable that the human race in the earliest stages of its evolution used natural tools without realizing their importance as means of adaptation. It is certainly true that the progress of the race in mechanical invention was at first very slow. Long ages elapsed before improvements were achieved which seem in the light of modern mechanics to be comparatively simple. The important fact is that the human race through social organization, and undoubtedly in large measure because of its ability to use

language, arrived ultimately at a clear recognition of the advantage to be gained by substituting weapons and tools for claws and teeth and physical strength. When the form of intelligence which made possible the evolution of the mechanical arts appeared in the world, it operated to make the human race master of the world in a way and to a degree not equaled by any other animal form.

Tools as evidence of complex cerebral processes.—The evolution of mechanics is directly related to facts which were reviewed in earlier paragraphs. Man has a large cerebrum in which impressions are rearranged and recombined. Without an inner world where impressions can be worked over into new arrangements, man would be like the lower animals dependent on simple instinctive impulses with very limited powers of readjustment.

Exchange as a manifestation of intelligence.—What has been said about tools can be repeated of other inventions which distinguish man from the lower animals. Man has a system of exchange. The animals have no exchange. An animal is utterly unable to rise to the level of purchasing and selling. Primitive savages did not come suddenly to the point where they used money and the other devices of exchange, such as weights and measures. Even the most primitive barter was, however, a very useful method of providing for social co-operation, and, once it was instituted, it supplied a method of adaptation so advantageous that the human race has elaborated exchange until it has become one of the most important of human activities.

Language the chief product of social intelligence.—The greatest achievement of man is the evolution of that chief instrument of social relations, language. The animals can make sounds and they use these sounds as a means of communication. The extent to which animals evolve in communication can be described by saying that through the imitations of sounds they convey to one another certain general ideas such as the ideas of food or of danger. Man has been able to go much further. He has evolved a medium of communication which is so complete that it has transformed his whole mode of life and his relation to the world in which he

lives by making social intercourse and the co-operative efforts which result from communication his chief method of adaptation.

Writing.—The inventiveness of man did not stop with the evolution of oral speech. After oral speech came writing. How arduous was the task of inventing and perfecting writing we learn from the history of the Orient and the Occident. The Chinese use even today a form of writing which is primitive and clumsy to such a degree that only the few can learn to read and write. The Chinese writing has no alphabet but expresses all of its root ideas by separate symbols. In order to read Chinese one must master some 40,000 different symbols. This is very probably one of the reasons why Chinese civilization, which was one of the earliest to appear and flourish, stagnated as contrasted with occidental civilization, which has enjoyed the advantages of a system of a flexible alphabetic writing, invented in Asia Minor by one of the semitic tribes and transmitted to the nations of the world as one of the most important inventions of all time. The alphabet is, no less than the mechanical arts, an achievement of intelligence. It was evolved in the inner world of man's consciousness. It has become an instrument of communication and adaptation superior to all others. Through the alphabet men record their findings in science and publish the policies of government. The world is different in many major respects since the alphabet was invented.

Number symbols.—To the discussion of the alphabet might be added the discussion of number symbols. So recent is the adoption of the symbols now used in this country and in Europe that we still acknowledge our indebtedness to a foreign source by calling the numerals "Arabic." The symbols which were in use in Europe before the Arabic numerals were imported, namely, the system of Roman numerals, were so clumsy that it is unthinkable that science and the great undertakings of modern industrial civilization would be possible if they were the only means of recording numbers. One needs only to try to multiply DLV by XIX to understand the clumsiness of the Roman numeral system.

Evolution through systematization.—Social psychology not only gives information about the beginnings of invention, but also reveals the more important fact that the mental capital of the race is steadily increasing. The increase is both through additions of new ideas and through the systematization of such ideas as we possess. It is hardly necessary to illustrate the way in which new ideas are accumulating. There is more justification for dwelling on the fact, which is often overlooked, that civilization makes progress by systematizing ideas.

Let us consider briefly one example of the way in which men have systematized experience. The words in our language which express some of the most fundamental and primitive ideas are typical of the earliest efforts to develop a language in that different sounds are used to express various aspects of the same fundamental idea. Thus we say "I am," "He is," "You are." "Am," "is," and "are" all express the same fundamental idea. This we state in modern grammar by saying that they are all forms of the verb "to be." The situation is very different when we deal with a verb of more recent origin. The verb "walk," for example, uses the same form for "I walk" and "You walk." It uses a very closely related form for "He walks." Not only so, but the past and future forms of walk are like the present in root form, while in the more ancient word we have to use different sounds when we say "I am," "I was," and "I will be."

Not alone the early verb forms are irregular; the same is true of adjectives with respect to their comparative forms. "Good" is an ancient word; it has a comparative form wholly different from the positive. The same is true of "Bad." The adjectives "New" and "Old" represent a later stage of language discrimination; their comparatives exhibit the same root form as the positive.

What is the meaning of the fact that ancient language forms are irregular and modern forms are regular? The answer to this question is that modern language has been systematized. When men first began to talk, they made a different sound in expressing

each idea. If that had gone on indefinitely, the time would have come when language would have become utterly unwieldy, even as the system of Chinese writing became unwieldy through the multiplication of distinct symbols. The mind of man confronted by this difficulty simplified somewhat the expression of ideas by adopting a system which brought together related forms of words.

The history of language is a record of devices which have been used to systematize language and human thinking. Some of the earlier forms were so clumsy that they have been abandoned. For example, the method employed in certain primitive languages to express the plural is to repeat the stem. In the language of the Dakota Indians "Runa" means a person, "Runa-runa" means the people. We have in the English language a much more economical way of forming plurals. Our method is the result of long racial experimentation. Another example of the same type is to be found in our use of the possessive case. The Latin language had a number of noun endings which were used to express possession. There were several declensions, as they are called, and the plural genitive was always different from the singular. All these manifold forms have been reduced to the lowest possible terms in English. We use a single device to express the possessive for singular and plural nouns, feminine nouns and masculine. Our language is highly systematized and is, therefore, a superior medium of expression.

Language as an instrument for systematizing experience.—Language has not only been systematized in its own structure, but it is the chief means by which man has systematized and recorded his thinking about the world. One needs only to be reminded of the importance of a clear-cut scientific terminology to realize how systematized language has been used by the human race to express and transmit the ideas by which scientific order has been brought into a world which seems to the senses to present the most bewildering confusion.

The contrast between man and the animals.—The foregoing discussions of tools and exchange and language illustrate in brief

outline the methods of social psychology and show how human adaptations to the world differ in method and in form from the adaptations to which the animals have attained in the same environment. Given the same world as that which meets the eyes of animals, man has reacted to it in a way which is a manifestation of his complex and highly evolved nature.

DISTINCTIVE CHARACTER OF HUMAN ADAPTATIONS

The special character of human evolution.—The general doctrine of evolution must be broad enough to include the unique facts of human life. Charles Darwin was so fully conscious of the special character of human evolution that he supplemented his great work on the *Origin of Species* by a book entitled: *The Descent of Man.* The social sciences have made some progress since the time of Darwin in arriving at a more adequate explanation of human evolution than did Darwin. Social science has, however, been overshadowed by biology and has at times been so dominated by biological methods of thought that it has lost sight of many of man's distinguishing characteristics. For example, there has appeared at times a disposition in certain quarters to minimize the importance of language and mechanical invention and even of human thought, and to seek an explanation of human life in the formulas which are satisfactory as explanations of adaptation among the lower animals. The civilized state has been compared to life in a beehive. The social tendencies among men have been attributed to an instinct which is called gregariousness and is supposed to be adequate to cement the members of a nation into a rationally organized society. Such attempts to explain a complex type of life by reference to lower forms of life fail to take advantage of the clear teachings of science. Human life is what it is because the evolutional processes have resulted in the appearance on the earth of one animal which is not wholly dominated by its instincts. Human life can be explained only when it is recognized that a large cerebrum has turned the course of evolution in the direction of the use of language and the cultivation of

skills which are far more complex than any which appear at the levels of life below man. The course of human adaptation is in a direction essentially different from that followed by evolution prior to the appearance of man on the earth.

Introspective psychology.—The distinctive character of human life and of the scientific methods of studying this life can perhaps be made clearer by referring to that branch of psychology which employs the method of introspection.

Historically introspection is the earliest method of psychological study. It consists in observing one's own mind at work. Aristotle employed this method and discovered the laws of memory and described these laws so accurately that his work has influenced thought through all the centuries following him.

Criticisms of introspection by behaviorists.—In recent years there has been a disposition in some quarters to look upon introspection as an utterly unsafe method of collecting scientific data. It has been pointed out that one is often misled by what he thinks he observes about his own mental processes. For example, when a person looks at some common object like a table, he actually sees only part of it. He supplies out of his past experience the items which are necessary to make his impression complete. He recognizes the table as having a familiar shape and familiar parts, some of which are eclipsed from his momentary point of view. Furthermore, he supplies ideas as to its use and value. The total present experience in this and other cases is a complex made up of sensations and memories. Because of the inability of people to distinguish between what they see and what they contribute, courts of law summon several witnesses whenever it is necessary to describe a scene with accuracy and completeness.

The pitfalls in introspective psychology are so numerous that a number of scientists have of late been advocating the abandonment of introspection altogether as a scientific method. They hold that the only objective way to understand human nature is to watch it in action. They call themselves behaviorists. They would limit the scientific study of man to purely external observations.

Such an extreme attitude on introspection is likely to be accompanied by a tendency to minimize the difference between human mental life, which can be in some measure reported through the use of language, and animal mental life, which can only be inferred by observing animal behavior.

Examples of introspective investigations.—In order to indicate the value of introspection it will be well to examine in detail a typical example of the use of this method.

If an observer fixes his gaze steadily on a point directly in front and gradually brings into the field of vision from the side a colored object, it will be observed that the object appears, when first seen, not in its true color and not with sharply defined outlines, but in an indifferent gray shade and as a very vague shape. We conclude from this observation, and very properly, that the retina is totally color-blind at the extreme periphery and incapable of clear discriminations. Further experimentation and observation of what goes on in consciousness reveals the fact that the field of vision has wholly different functions in its different parts. The margin of the retina is the part of the eye which warns us that something is going on in the world at the right or left of the center of clearest experience. If we turn our eyes or head in the direction indicated by the warning, we find that experience changes in character. When we look straight at an object we see what we could not see when it was in the edge of the field, namely, its color and its shape.

In such a case as this, introspection is of assistance not only to psychology but also to physiology. The meaning and importance of many of the structural differences of our organs of sense and of the central nervous system can be inferred from introspection when they would be extremely difficult to discover from mere external examination.

In the sphere of feelings, where we experience likes and dislikes, in the world of dreams and in the play of fancy, we find that introspection is the only method which we can employ to reveal the inner happenings of individual life. It is not to be

thought that introspection in these cases reveals all of the facts which science uses in formulating scientific explanations, but introspection gives us an indispensable body of data which are necessary for the complete study and understanding of human life.

Experimentation combined with introspection.—If we think of modern psychology as combining the introspective method with the experimental method, we shall remove the objections which have been advanced against the direct observation of one's mental processes. Indeed, careful introspection is as legitimate as any form of scientific observation. It may lead and has led to important knowledge. When Aristotle formulated the laws of memory he had no help from the science of brain physiology and he had none of the techniques of modern experimental psychology. Yet he made a very useful and accurate formulation of some of the most fundamental laws of human nature.

SUMMARY.—We come back by way of final summary to the point made at the beginning of this chapter. The inner experiences of human beings are profoundly different from the facts and forces which are dealt with by the physical sciences. The laws of human nature are expressions of a higher form of organization than appears elsewhere in the world. There is nothing more complex or more highly integrated than human thinking. There is nothing more original in the world than human combinations of ideas. In making these assertions there is no disposition to remove man in his physical or mental life from the world in which he lives or from the evolutionary series to which he belongs. Man is a product of the evolutionary process. He is, however, greatly superior, in the powers which he exhibits, to all other animals, just because the evolutionary process has resulted in the appearance in the human race of highly complex nervous structures and correspondingly complex methods of adaptation. In the case of man there has appeared as the essential fact in his bodily equipment a larger and more highly organized cerebrum than that possessed by any other animal. In this cerebrum sensory and motor impulses unite in associative combinations. In every nor-

mal human being there is an inner world of ideas and of recognitions of values, for which inner world of rational thought there is no counterpart in the world studied by the physicist or in life below the human level.

SELECTED REFERENCES

1. Emory S. Bogardus, *Fundamentals of Social Psychology* (Century Co., 1924), pp. xiv+479.

2. Edward Stevens Robinson and Florence Richardson-Robinson, *Readings in General Psychology* (University of Chicago Press, 1923), pp. xvi+674.

3. Charles H. Judd, *The Psychology of Social Institutions* (Macmillan Co., 1926), pp. ix+346.

4. C. Judson Herrick, *An Introduction to Neurology* (3d. ed., W. B. Saunders Co., 1922), pp. 355.

5. C. Judson Herrick, *Brains of Rats and Men* (University of Chicago Press, 1926) pp. xiii+382.

5. Richard Swann Lull *et al.*, *The Evolution of Man* (Yale University Press, 1922), pp. x+202.

GLOSSARY

Abiogenesis.—The doctrine that living matter arises today from the synthesis of inorganic materials apart from already existing organisms.

Acid.—A substance that in solution forms hydrogen ions (H^+), often tastes sour, and forms salts with bases.

Adaptation.—Organic fitness. The adjustment in form or function of the organism to the environment.

Algae.—Primitive water plants.

Alkali.—The strongest bases, such as sodium hydroxide and potassium hydroxide, are called alkaline bases or alkalies.

Allantois.—One of the embryonic membranes of land vertebrates used largely as a temporary lung.

Allelomorphs.—Contrasted unit character inherited according to Mendel's Laws; the contrasted genes that are the differentials of such characters.

Amino acid.—One of a number of organic acids containing the NH_2 radical. The "building stones" of proteins.

Amnion.—One of the embryonic membranes of the land vertebrates. This membrane is a fluid-filled sac surrounding the embryo.

Amphoteric.—Substances (like many proteins) that can absorb and therefore neutralize either acids or alkalies.

Anion.—The negatively charged ion of an electrolyte.

Antithrombin.—A substance that renders thrombin inactive.

Anus.—The posterior opening of the gut or digestive tract.

Aphasia.—Loss of ability to speak or to understand written or spoken words.

Atom.—The smallest particle of an element, about 2×10^{-8} cm. in diameter.

Atomic number.—This is also called the ordinal number. The atomic number of an element represents the excess electro-

positive charge on the nucleus of its atoms, or, the number of electrons encircling the nucleus.

Auditory.—Pertaining to hearing.

Autosome.—One of the chromosomes of a cell other than the *X*- and *Y*-chromosomes.

Axon.—An elongated process or branch of a nerve cell that usually conducts impulses from the cell body.

Basal metabolism.—The rate of oxidation in an animal at rest.

Base.—The most common bases are hydroxides which in solution form hydroxide ions (^-OH). A base combines with acids to form salts.

Base-forming.—A base-forming substance which is convertible into a base, for instance, by combination with water; ammonia, NH_3, and metal oxides, such as calcium oxide, CaO, are instances.

Bilateral symmetry.—Having one lateral half of the body approximately the mirror image of the other half.

Blastula.—A stage in the embryology of animals; typically a hollow globe of cells with the wall usually one layer thick.

Calorimeter.—An instrument for accurate measurement of heat production in combustion, or animal oxidation.

Carbohydrate.—One of a class of carbon compounds commonly found in protoplasm, such as starches, sugars, cellulose, etc.

Cation.—The positively charged ion of an electrolyte.

Centrosome (central body).—A minute body in animal cells that lies near the nucleus and plays a rôle in mitosis.

Cerebellum.—The anterior part of the hind-brain, devoted largely to the function of muscular co-ordination.

Cerebrum.—An enlarged portion of the forebrain in vertebrates; commonly in the form of a pair of cerebral hemispheres.

Chlorophyll.—The green coloring matter found in plants and some animals.

Chordate.—A member of the phylum Chordata, characterized by having a notochord, pharyngeal clefts, and a dorsal tubular nervous system.

Chromatin.—The deeply staining matter of the nucleus, made up of genes and other substances.

Chromosome.—One of the separate masses of chromatin, made up of a particular set of genes, together with other substances.

Cilia.—Minute hairlike structures covering the surface of certain cells, as in Paramecium.

Cleavage,—Subdivision of the egg cell into smaller cells.

Coelom.—The main body cavity which typically surrounds the digestive tract and is lined by a special connective tissue layer.

Colloid.—A mixture in which particles larger in size than molecules are held in suspension in a liquid.

Compound.—A pure substance which represents a chemical combination of two or more elements.

Cretinism.—The condition of stunted growth and general debility following failure of the thyroid glands in the young.

Cytosome.—The non-nuclear protoplasm of a cell. *See* Nucleus, Protoplasm.

Dendrite.—A branch or projection from the body of a nerve cell ordinarily conducting impulses to the nerve cell.

Diabetes.—A disease caused by failure of production of the hormone insulin by the pancreas.

Differentiation.—A process in development, involving the appearance of structurally or functionally specialized parts.

Diploblastic.—Composed of but two germ layers, ectoderm and endoderm.

Diploid.—Referring to the double set of chromosomes present in body cells and in germ cells before meiosis. *See* Haploid.

Dominant character.—A character that expresses itself in the presence of a recessive gene. *See* Recessive character.

Dorsal.—Pertaining to the back, usually the upper surface of an animal. In man it may be synonymous with posterior, but this is not the case in most animals.

Ectoderm.—The outer germ layer of a gastrula or later embryo.

Electrode.—The positively charged (anode) or negatively charged (cathode) plate or wire from which an electric current passes into a solution, or into which a current passes from a solution.

Electrolysis.—The passage of an electric current through a solution of a chemical compound accompanied by the decomposition of the compound by the current at the electrodes.

Electrolyte.—A compound which is capable of conducting an electric current through a solution. It does so by forming positive ions (Na^+, etc.) and negative ions (Cl^-, etc.) which carry the current.

Electron.—The smallest particle of negative electricity, with a diameter of about 2×10^{-13} cm. (The proton is sometimes called a *positive electron.*)

Endocrine glands.—Glands without ducts, that build up useful substances (hormones) and pass them into the blood.

Endoderm.—The inner germ layer of a gastrula, or the tissues derived from it.

Enzyme.—An organic substance, produced by living cells, that accelerates chemical action. Though it is not used up in the process, it may temporarily participate in the reaction; e.g., pepsin in gastric digestion.

Factor.—A genetical term, equivalent to gene.

Fauna.—Collectively, the associated animals of a given region or period of time.

Fertilization.—The process of union of gametes to form zygotes.

Frontal.—Toward the superior end of an animal.

Galaxy.—A vast disklike aggregation of 1,000,000,000 stars, of which the sun is simply one unit.

Gamete.—A cell which unites with another cell to form a zygote. Typically, an egg or a sperm.

Ganglion.—A mass of nerve cells functioning as the organ of nervous control of a region of the body.

Gastric.—Pertaining to the stomach.

Gastrulation.—That process in the developing embryo by which the two-layered condition is produced. The formation of a gastrula.

Gene.—The differential substance in a germ cell or other cell that determines a given character peculiarity. *See* Factor.

Germ layers.—The primary layers of cells in a developing embryo; ectoderm, endoderm, and later, mesoderm.

Germ plasm.—The total of the hereditary material in germ cells. More particularly, the chromatin.

Glycogen.—Animal starch.

Gonads.—The ovaries and testes.

Gonadectomy.—Removal of the gonads (ovaries or testes).

Gyrus.—A wrinkle or convolution of the surface of the cerebral cortex, bounded by sulci or fissures.

Hemoglobin.—The iron containing protein in the red blood cells that acts as a carrier of oxygen.

Hemophilia.—Decreased coagulability of the blood.

Heterozygous.—Referring to an individual having in its germ cell both a dominant and a recessive gene of the same allelomorphic pair. Hybrid with regard to any pair of allelomorphs.

Homologous.—Said of parts or organs that have the same embryological and phylogenetic origin.

Homology.—The similarity of structure and development of organs and parts.

Homozygous.—Referring to an individual with two doses of the same gene or allelomorph.

Hormone.—A substance secreted by a ductless (endocrine) gland into the blood stream. It usually acts as a controller or regulator of general or specific cell functions.

Hypertrophy.—Exceptional overgrowth of a part or an organ.

Inhibition.—Decrease or total suppression of a physiological process.

Invertebrate.—Any animal without a backbone.

Ion.—A positively or negatively charged atom or group of atoms (e.g., NH_4^+, $SO_4^{=}$). Solvents like water cause the separation of the positive and the negative ions into mobile ions (ionization).

Ionization.—Separation of positive and negative ions by solution, by heat, etc.

Isotopes.—Varieties of an element whose atoms have the same atomic number but different atomic weights.

Mammal.—A vertebrate animal with hair, differentiated teeth, and with mammary glands, etc.

Maturation.—That process in the germ-cell cycle during which the chromosomes are reduced from the diploid to the haploid number. *See* Meiosis.

Medulla.—Abbreviated from medulla oblongata, a part of the hind-brain.

Meiosis.—*See* Maturation.

Metazoa.—Many-celled animals with tissues.

Mitosis.—The usual process of cell division which involves the formation of spindle fibers, and in which each chromosome is equally divided lengthwise so that each daughter-cell gets equal shares of the germ plasm.

Molecules.—The smallest particle of an element, or of a compound, that exists in a free condition. (Note that a molecule of the element may consist of a single atom (He), of two atoms (H_2) or of more than two atoms.)

Mutation.—An inherited change in the germ plasm producing changes in the soma, or body.

Myxedema.—The depression and degeneration following failure of the thyroid glands in adults.

Natural selection.—The name of Darwin's theory of evolution—paraphrased as "the survival of the fittest."

Neuron.—A nerve cell and all of its processes, which may be very long.

Notochord.—A cylindrical rod of cells ventral to the nervous system. It is the first stage in the development of the vertebral column of vertebrates; usually present only in embryos.

Nucleus.—The central differentiated region of most cells that contains the chromatin.

Ontogeny.—The development of an individual, as contrasted with phylogeny, the evolution of the race.

Ovary.—The organ that produces eggs, or ova. The female gonad.

Ovum.—The egg cell ready for fertilization, or early development after fertilization.

Pathologic.—Abnormal, or diseased.

Phylogeny.—*See* Ontogeny.

Phylum.—One of about a dozen major groups of the animal kingdom or of four major groups of plants.

Pituitrin.—A substance obtained from a region in the hypophysis gland.

Placenta.—An organ, highly vascular in character, that acts as a nutritive intermediary between the fetus and the mother. It is characteristic of mammals, and most complex in the apes and man.

Planet.—One of the eight relatively small bodies, such as the earth, that revolve around the sun.

Plasma.—The fluid part of the blood.

Polar.—A term used to indicate electric dissymmetry, as one atom or group of atoms in a molecule being electro-positive (forming a positive pole), another being electro-negative (forming a negative pole).

Polarized light.—According to the wave theory of light, polarized light consists of vibrations in a single plane. Certain substances, such as lactic acid, glucose, etc., have the property of turning this plane to the right (dextro-rotary, abbreviated d-) or to the left (laevo-rotary), when polarized light passes through their solution.

Protein.—A type of organic substance mainly composed of groups of amino-acid molecules.

Proton.—The smallest particle of positive electricity with a diameter of about 10^{-16} cm.; it is sometimes called the positive electron; the nucleus of the hydrogen atom represents a proton.

Protophyta.—One-celled plants.

Protoplasm.—The complex of chemical substance in which life inheres.

Protozoa.—One-celled animals.

Radial symmetry.—An arrangement of similar parts around a median axis, as in a jellyfish.

Recessive.—One of a pair of contrasting characters in heredity that cannot express itself, or only slightly expresses itself, in the presence of the dominant allelomorph.

Reflex action.—An action performed as the result of an impulse which passes over a reflex arc.

Reflex arc.—A group of two or more neurons, one of them sensory, another motor, so connected as to transmit impulses resulting in reflex actions.

Respiratory center.—A group of nerve cells in the medulla acting together as a reflex and automatic center for the process of respiration.

Retina.—The nervous elements inside the eye stimulated by light.

Salt.—An ionizable compound (e.g., $Na^{+}Cl^{-}$) formed by the interaction of an acid (e.g., $H^{+}Cl^{-}$) and a base (e.g., $Na^{+-}OH$).

Satellite.—A body, such as the moon, that revolves around a planet.

Secretagogues.—Substances initiating or augmenting secretions by glands.

Sensory.—Pertaining to sensation.

Soma.—The body, as opposed to germ plasm.

Somatic.—Referring

Spinal animal.—An animal in which by disease, trauma, or surgery the whole or a part of the spinal cord is separated from the brain.

Star clusters.—Aggregations of stars ranging from a few hundreds to 100,000.

Stars.—Suns that are so distant that they appear to be points of light.

Sun.—The great center of the solar system, more than 1,000,000 times the volume of the earth.

Synapse.—A point of contact of two neurones.

Synapsis.—The pairing of maternal and paternal homologous chromosomes during maturation or meiosis.

Testis.—The organ that produces sperms. The male gonad.

Tetany.—Tremors and convulsions following the removal or failure of the parathyroid glands.

Thrombin.—A substance that causes clotting of blood by crystallization of one of the blood proteins (fibrinogen).

Thyroglobulin.—The hormone secreted into the blood by the thyroid glands.

Tissue.—A group of cells of similar structure and function that make up a continuous mass or layer.

Traumatic shock.—A condition of profound depression following extensive body injuries.

Triploblastic.—Referring to the embryo or adult with three primary germ layers: ectoderm, endoderm, and mesoderm.

Tropism.—A reflex action of an entire organism.

Vagi nerves.—A pair of nerves in the neck that connect the hind-brain with the esophagus, lungs, heart, stomach, and small intestines.

Valence.—The *positive valence* of an element represents the capacity of its atom to combine with one, two, three, or more atoms of chlorine, or with the equivalent amount of oxygen ($O^{=} = 2Cl^{-}$). Thus Al^{+++} is *trivalent*, forming $Al^{+++}Cl_3^{---}$ or $Al_2^{+++}O_3^{=}$. The *negative valence* of an element represents the

capacity of its atom to combine with one, two, or more atoms of hydrogen. Thus oxygen is *bivalent* in water, H_2O.

Valence electrons.—The electrons in the outermost shell of an atom, which by their escaping from the atom, or by the increasing of their number in the atom, make chemical combination possible.

Vaso-motor center.—A group of nerve cells in the medulla acting together as a reflex center in the control of the tonus of the blood vessel musculature.

Ventral.—Literally, pertaining to the belly; hence usually the lower part of an animal.

Vertebrate.—An animal with a backbone.

Vitamine.—Organic substances in foods different from the ordinary proteins, fats, and starches, and serving important rôles in general and specific living processes.

Zygote.—A cell (or individual) produced by the union of two gametes. Commonly, the fertilized egg.

INDEX

INDEX